AN INTRODUCTION TO STRATIGRAPHY

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BRITISH ISLES

BY

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TO

DOCTOR PIERRE PRUVOST, F.M.G.S.

autrefois Professeur de Geologie a l'Universite de Lille (France)

WHOSE WHOLE-HEARTED FRIENDSHIP DID SO MUCH TO MAKE PLEASANT THE AUTHOR'S EARLY PATHS IN GEOLOGICAL RESEARCH

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PREFACE TO THE THIRD EDITION

Whilst it is a source of both pleasure and gratification to me that the demand for this little book continues unabated after a run of thirty-three years, its revision for a new edition presents a common problem—how much to alter, how much to leave unaltered.

In the first place it is surprising how many of my generalizations, especially the reconstructions of the geography of past epochs, have stood the test of time and seem to require little alteration. The long-continued work of Professor L. J. Wills in this field has extended the picture into neighbouring parts of Europe but does not appear to necessitate any obvious changes in the details I have given. My original maps have accordingly been retained.

In the second place many of the references in the original work were to papers then recently published. I have left those which refer to papers which have since become classics or where controversial points were discussed. I have added references to recent summaries and work of far-reaching significance, but here, it may be noted, the student has now readily available the eighteen parts of *British Regional Geology* published officially at a low price by Her Majesty's Stationery Office, and including the latest information available to the officers of the Geological Survey. No one seriously studying geology should fail to acquire this series together with the magnificent map, in two sheets, on the scale of 1:625,000 (roughly 10 miles to the inch) published as part of the National Planning Series by the Ordnance Survey. Unfortunately the Drift map on the same scale, long promised, is still in preparation.

My brief notes on economic geology I have left but it should be noted that in so far as our major mineral resource—coal—is concerned there now exists *The Coalfields of Great Britain* edited by Sir Arthur Trueman. The relationship between geology and scenery I have developed in my own *Britain's Structure and Scenery* (Collins' *New Naturalist Series*).

As I said in my note to the reprint of 1950 some important advances in knowledge resulted indirectly from the Second World War. An intensive search for possible home resources of oil and other minerals led to the drilling of numerous deep borings which have added greatly to the

knowledge of the underground structure of south-eastern England, though the major features outlined in this book have not been fundamentally changed. Deposits of Permian potassic salts of the types famous at Stassfurt were proved to underly Eskdale in North Yorkshire thus confirming the geography of the period shown in *Fig*. 42. Unfortunately the deposits have proved economically unworkable at present. The principal oilfield proved and worked is that at Eakring in Nottinghamshire, with the oil in rocks of Millstone Grit age. Since the oil has probably migrated from a lower horizon this discovery adds little to our knowledge of past geographical conditions.

The greatest advances in knowledge have been amongst the oldest and the youngest rocks. The perfecting of methods of dating by radioactive minerals enables a time sequence to be worked out in the complex Archean rocks. If Professor H. H. Read's revolutionary views on the nature and origin of many granites come to be generally accepted much reinterpretation of pre-Cambrian geology will be involved. For more than a century the Highlands of Scotland have provided a battleground for structural geologists and here Professor W. Q. Kennedy has made a major advance by demonstrating extensive lateral displacement along the Great Glen fault.

At the other end of the geological time scale pollen analysis and radioactive carbon studies have introduced precision in the dating of post-glacial deposits. The development of techniques of geomorphological analysis has come to the aid of the geologist in tracing geographical changes where no deposits exist.

These points are mentioned to indicate how much still remains to be discovered even in the well worn paths of British geology.

L. D. S.

London.
October 24th, 1955.

PREFACE TO THE SECOND EDITION

It is with peculiar pleasure that I have undertaken the preparation of a new edition of my "Introduction to Stratigraphy." It was my first full length book, and, although I have since become responsible for a number of others, none has given me greater pleasure in the writing. Its popularity with the students for whom it was written has given me real pleasure; on the other hand, my methods have not received the condemnation I first feared from experienced teachers. Instead, a much more elaborate study of the evolution of Britain has since appeared, and a French colleague, quite independently, has attacked the study of the geographical evolution of continental Europe along the same lines. I take it as a compliment, too, that one of our leading professors (recently deceased) commended it to his students provided they remembered it ought to be called "The Deadly Stamp."

Scarcely less has been my enjoyment of the battles waged over some of the more controversial matters of necessity dealt with herein. These battles in print have done much to cement friendships with my opponents and to clarify my own ideas. Where an important question still remains unsettled, I trust my readers will find I have fairly stated both sides. In the first edition I admit having taken a deliberately partisan attitude, but maturer reflection has convinced me that, in a text-book, this may be unfair to the student.

I should like to take this opportunity of expressing my sincere thanks to many friends and colleagues for calling my attention to matters requiring alteration or consideration. In the first place to my colleagues, Dr. A. K. Wells and Dr. S. W. Wooldridge—staunch friends and able critics; to Professor S. H. Reynolds for a careful list of suggestions; to Dr. R. H. Rastall, Dr. T. Franklin Sibly, Dr. L. F. Spath, Professor A. E. Trueman, the late Professor J. W. Gregory, Professor H. H. Swinnerton and the late Dr. J. W. Evans for pertinent comments. Mr. S. H. Beaver has been responsible for seeing the book through the press.

In this edition I have endeavoured also to incorporate the results of recent work: a number of sections

have been re-written, a number of illustrations altered and seventeen figures added.

L. DUDLEY STAMP.

New York,
November, 1933.

PREFACE

There are at least two ways of approaching the study of most sciences. One is to work from cause to effect, the other from effect to cause. For the most part the hapless student of Stratigraphical Geology has been burdened with long catalogues of disconnected facts which are really the " effects " or results of comparatively few simple causes. He has been expected to remember " successions " in varied, often obscure and imperfectly known localities of his own and other countries, thicknesses of strata, their lithological characters and lists of their fossil contents. Too often he has been left to form some connected idea of the whole almost unaided, still more often he has been left with but a very vague idea of the causes of the phenomena recorded, or of the general conditions prevalent at the time of formation of the beds in question.

It is perfectly true that the unravelling of the tangle of the world's geological history has proceeded by the laborious and painstaking observation of a myriad small details, but that is no reason why the elementary student should be dragged over the same thorny paths. No beginner in Chemistry would be told details of the numerous experiments by which the older workers established the identity of an element and be left to deduce therefrom the characters of that element. Instead the chemist first learns the general nature of the elemental substances, and so, almost unconsciously, learns to anticipate their behaviour towards one another. When he has firmly grasped these principles he is in a position to appreciate the details of experimental research. He may afterwards learn that the element in which he so firmly

believed is probably a compound, that the molecule on which his whole conception of chemistry was founded may have no real existence. No matter, he will then be in such a position that the structure of facts, originally held together by his early theoretical conceptions, will not seriously be endangered by an alteration in hypothesis, however fundamental. In very much the same way the writer believes that the time has come for the study of stratigraphical geology to be attempted on the same lines. From the patient research of four or more generations of geologists, we have now a very fair idea of the conditions prevalent during each of the great geological periods, and, at least so far as the later periods are concerned, a tolerable conception of the relative distribution of land and sea. The writer is convinced, largely from experience, that once the student has formed a mental picture of the conditions prevalent at some remote geological epoch—let the picture be, for example, that of a mountain-girt desert basin, swept by wind storms and occasional torrential rains—in which features and boundaries are fixed by reference to existing points on the earth's surface, he will *know* automatically what type of beds to expect, in what direction the beds thicken and at least the probable character of their fossil contents.

Along almost exactly the same lines, geographers have made this fundamental change in their methods of teaching within the last decade. One now no longer learns long lists of capes, bays, towns and the products of some—probably temporary—political unit, but, with a clear and brilliant conception of the world divided into "natural regions," each with its own climatic, topographic and edaphic features, the natural products and industries suggest themselves almost automatically.

It is not, of course, claimed that the method of treatment is wholly new, such a claim would be absurd with books like Jukes-Browne's "Building of the British Isles" in existence, but the originality of the book lies in the presentation of the rudiments of English Stratigraphical Geology in this manner to beginners.

The writer craves especially the indulgence of older geologists. He is perfectly aware of the numerous pitfalls which lie in the path of one who approaches the sub-

ject in this way. In escaping from the Devil—lists of fossils and tables of thicknesses certainly are satanic—the deep blue sea of over-generalization and of theory unsupported by facts may prove equally fatal. Perhaps some of the palæogeographical maps of the World in the early Palæozoic periods which have been published during the present century are the most glaring examples of the fatal effects of the deep blue sea. Still, there is a *via media,* and the writer feels convinced that a mass of facts which has been assimilated as a natural result of a vivid mental picture of the causes will be likely to remain even if the picture be afterwards seen to be faulty in many respects.

In the references to the Palæontological side of the subject, emphasis has been laid especially on the general character of faunas, their separation into groups, their relation to one another and their movements rather than on the individual species of fossils characterizing each particular bed.

Having thus sketched the outlook of the book, a few remarks may be added concerning its scope.

It is written primarily for those taking Geology as one of the subjects for a Degree of a British University. An attempt has also been made to render it a serviceable text-book for those specializing in Geology or entering for an Honours Degree, by the introduction of detailed matter in smaller type and by the inclusion of references. It must not, however, be presumed that the part in smaller type is not of general importance. It is always difficult to tell an Honours candidate what to read in the matter of original work. It is to some extent dependent on the student's natural tastes, to a large extent on the personal interests of the teacher. In this book references have been limited to those papers which could be profitably read by any senior student. As far as possible they have been restricted to publications in well-known journals: papers appearing in the Transactions or Proceedings of local Natural History Societies, however valuable, are so frequently inaccessible to the student that it seemed better to ignore them. Again, references to such papers as afford merely a verification of some point of interest and are not of general importance have also

been omitted. This selection of references may seem arbitrary, but a recent and more complete bibliography is now available in the "Handbuch der Regionalen Geologie," Band III., Abteilung i., The British Isles (1917-8). This work has since been revised and published in two volumes by Messrs. Thos. Murby & Co. The first, a "Handbook of the Geology of Ireland," is by G. A. J. Cole and T. Hallissy, the second, a "Handbook of the Geology of Great Britain," is by a number of authors.

An apology is tendered to very many authors who will find their work incorporated herein without its source being indicated. As far as possible special assistance and the incorporation of unpublished work has been acknowledged, but it was feared that the multiplication of references to the varied sources of information utilized in the compilation of this book would confuse the student. The author, however, wishes to express his special indebtedness to the "Handbuch der Regionalen Geologie."

Special attention is drawn to the maps and diagrams which illustrate this book. They are just as essential to the work as is the text. In the same way that a clear mental picture of former conditions is essential to an understanding of the beds now extant, so a diagrammatic representation of the relations between beds or a sketch-map of the geography of a given period conveys far more to the mind than pages of description. The diagrams and maps in this work should be photographed mentally, for the most part the information contained in them *is not repeated in the text.* To secure uniformity of treatment and style, and especially to accommodate them to the size of a single page, most of the illustrations are original, though many are redrawn from the published works of various authors. The source of such is indicated.

Whilst the scope of this book is in the main limited to rocks as developed in the British Isles, the author has not hesitated to treat the North-West of Europe as a whole, or to include a description of other localities when such a procedure seemed indispensable to the proper understanding of the British deposits.

The reader is presumed to have a knowledge of the principles of Physical Geology. In the chapter headed

"Introduction" only certain aspects of the subject are touched upon — such aspects as are not always to be found detailed in works on Physical Geology.

In its earlier stages, the writing of this book occupied the leisure of a voyage to Burma, in its later stages —especially in the preparation of the diagrams—it has helped to relieve the tedium of inevitable delays whilst travelling in the jungles of Upper Burma. Anxious hours of waiting for the arrival or non-arrival of one's bullock-carts or one's dinner have thereby passed almost unnoticed, but to these circumstances some of the imperfections of the work must be ascribed.

The author would be very grateful for any corrections, suggestions or constructive criticism which would make for the improvement of a second edition, should such become possible. Correspondence may be addressed to him care of the Publishers. The author wishes also to take this opportunity of expressing his warmest thanks to his former colleague, Mr. A. K. Wells, and to his successor at King's College, Mr. S. W. Wooldridge, for their help in many directions whilst the book has been passing through the press. Most of the ideas embodied in this work were developed during the eight years which the writer spent at King's College (London) under the influence and ready sympathy of Professor W. T. Gordon.

L. DUDLEY STAMP.

Yenangyaung, Burma.
1922.

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CHAPTER I.

INTRODUCTION.—SOME PRINCIPLES OF STRATIGRAPHICAL GEOLOGY.

I. GENERAL.

Stratigraphy is another name for Historical Geology. It is so called because it is chiefly concerned with the stratified rocks which, by careful study, can be made to tell the story of the earth. In this sense Geology, especially Stratigraphical Geology, is "Geographical Evolution," and the study of Stratigraphy has for one of its principal objects the tracing of the changes in the geography of the globe through the different periods in its history.

Two fundamental principles underlie Stratigraphy—

1. The Law of Superposition.

Where one bed of rock rests on another it is presumed that the upper bed has been laid down after the lower, and hence is younger. This is true

a. for all sedimentary rocks,

b. for extrusive igneous rocks -lavas which have been poured out at the surface, and beds of ashes,

always provided that the original order has not been reversed as a result of folding or faulting or other disturbance. In other words, "In any succession of beds each one represents the conditions which prevailed over a certain area for a certain length of time, the lowest is the oldest, the uppermost is the newest, and the relative age of the others is indicated by their relative position." Now the upper bed in one locality when traced laterally may be found to underlie one or more beds in another locality, accordingly the higher beds in the latter locality are still newer. In this way a whole succession of strata

might be built up from the very oldest to those being formed at the present day. But certain great difficulties present themselves :—

a. Owing to earth-movements which have taken place during the Earth's history and to the processes of denudation which commence as soon as—or even before—the land appears above the surface of the sea, beds present in one locality may be absent in another, and in the latter there is a gap in the succession. Such a gap may indicate that the region concerned formed part of a land-mass at that time, or merely that the region came under the influence of submarine denudation for a time.

b. One bed when traced laterally may change its character, and unless the whole gradual change can be traced it is very difficult to say whether a bed—for example of sandstone—in one locality was formed at the same time as a bed—perhaps of limestone—in another.

c. Beds can, as a rule, or very frequently, only be observed in scattered localities—for example, though beds of very similar character occur in England and on the Continent, they cannot, with one or two possible exceptions, actually be traced from one area to the other.

2. The Law of Strata Identified by Fossils.

Fossils are remains or traces of former organisms. It has long been known that strata of different ages are characterized by different faunas or suites of fossils. This was once thought to be due to a number of separate creations, each of which had been overwhelmed and buried by the masses of sediment in which it is now found. Suffice it to say for the present that we now know that in each period of its history, the earth was populated by a different series of creatures, although the differentiation is not due to separate creations, but to evolution. When once it dies out (or becomes "extinct") a species does not reappear. It follows that a limestone in one district and a sandstone in another may be "correlated" or assumed to be of the same age from a study of the fossils of the two beds. Thus the deter-

mination of the relative age of the sedimentary rocks depends ultimately on their fossil contents.

II. *GEOLOGICAL TIME.*

Time is continuous. There are certain natural phenomena which serve to divide time into definite units. The phenomenon of day and night serves to define one unit of time—the day; the movement of the earth on its orbit round the sun defines another—the year. But larger units than that are difficult to define. The historian frequently takes the time between two important events as an era, or, in a sense, as a unit of time, although he is still able to measure in years the space of time so defined. The prehistorian is no longer able to measure his eras so accurately, his units of time become very approximate. The geologist, in his turn, has to deal with the vast period of time which elapsed before man appeared on this globe. The length of time with which he deals is so enormous and the records so meagre that measurement by such a small unit as a year is generally impossible. No one would hand a traveller going on a long sea voyage a six-inch ruler and ask him to measure the distance between the islands and points of importance sighted during the trip. Yet the voyager, by careful observation of all features seen on the way, might be able to give a very fair account of the relative distance between points passed as well as of the chief characteristics of the lands sighted. Similarly it is equally absurd to ask a geologist to measure time in years. It does not follow, however, that he cannot have a very fair conception of the main events in the world's history and the relative time of their occurrence.

In recent years a method of estimating geological time in years has been devised and used with some amount of success. There are certain elements—radioactive elements—which undergo disintegration at a constant but very slow rate. The actual rate can be and has been measured. When a minute crystal of a radioactive mineral is enclosed in a larger crystal of certain other minerals—such as the dark mica, biotite—the emanations of ultra-microscopic bodies which are the result of the slow disintegration of the radioactive substance produce a marked change in the surrounding mineral. When seen

in thin sections under the microscope the size of the zone of alteration (" pleochroic halo ") affords a means of measurement of the time which has elapsed since the original formation of the rock. This method is, of course, restricted to the igneous rocks in which radioactive minerals occur. Another method is by very accurate chemical analysis showing the relative proportions of unaltered radioactive substance and the final " end product " of its disintegration. This again permits the calculation of the time which has elapsed since disintegration commenced.

Thus, whilst the Petrographer and the Petrologist are concerned with the description and interpretation of the different types of rock which compose the Earth's crust, the Stratigrapher is concerned with their relation one to another in point of age and the delineation of the conditions under which they were formed. There must have been a primeval crust of the Earth before the advent of life. Whether the oldest crystalline rocks are remnants of this original crust is another matter. Little really definite can be said of the age relationships between the different members of these old crystalline rocks, except in individual regions, and thus the Stratigrapher is mainly concerned with the overlying rocks in which traces of life are preserved.

In exactly the same way as the student of early history, when once he has fixed definitely the date of certain important events, is able to use a variety of evidence in reconstructing the history of the intervening period, so the Stratigrapher, when once a past era of the earth's history has been fixed by a definition founded on a study of the remains of organisms then living, is able to use a variety of evidence in reconstructing the history of that period.

But geological time is no exception to the general rule. It is continuous, and any attempt to divide it into eras or smaller periods must really result in an artificial division. Events of great importance in one part of the earth's surface may never have affected other parts. In defining such periods it is very desirable to make the divisions as obvious and as natural as possible. Thus one might define a period of English History as from the Invasion of William I. in 1066 to the Battle of Waterloo

in 1815. Both are important events of worldwide importance. But it is just conceivable that a person of narrower outlook, having the desire for greater accuracy, might base his definition on one incident in the lives of the principal actors in these great events. But the period from the hour of birth of William I. to the hour of death of Napoleon I., though a very accurately defined period, would be wholly artificial and almost without significance. Thus it is necessary in Geology to avoid defining the duration of some period as from the first appearance of one particular species of fossil to the last appearance of another, and thereby to ignore some great event of worldwide significance. There is, unfortunately, a growing tendency in this direction amongst certain specialists in Palæontology. There is thus often a difference of opinion as to the exact limits between the units of geological time or rather between the rocks deposited during those units of time. In this book the limits adopted depend on

a. Laws of Priority—the meaning or definition intended by the originator of the period defined.

b. Palæontological Phenomena, especially the consideration of a whole group or a whole fauna. The limit is marked when possible by a "faunal break."

c. Structural Phenomena, utilizing wherever possible any great change in the conditions of the earth's surface, such as widespread folding movements, etc. In other words, the limit is marked in most regions by a "break" or unconformity.

d. Practical considerations; it is almost useless to have a limit which cannot be traced among rocks in the field.

Geological time is divided into five great Eras, and into a number of Periods. The rocks deposited during a Period constitute a System.

Era.	Period or System.
QUATERNARY	Recent or Holocene Pleistocene
KAINOZOIC, CENOZOIC or TERTIARY	Pliocene Miocene Oligocene Eocene

Era.	Period or System.
MESOZOIC or SECONDARY	Cretaceous Jurassic Rhætic Trias
PALÆOZOIC or PRIMARY	Permian Carboniferous Devonian Silurian (Gotlandian) Ordovician Cambrian

EOZOIC or PRE-CAMBRIAN or ARCHEAN.

A System of rocks usually comprises several Groups or Series or Stages. The smallest division of geological time is a *hemera,* and the rocks deposited during a hemera constitute a zone. Some further details of these smaller divisions will be given later. The term " formation " is an old one, usually applied to a lithological division, *e.g.*, the Chalk Formation. The British Isles are exceptionally fortunate in having representatives of practically all the Systems.

III. OROGENIC OR TECTONIC PHENOMENA.

Modern seismic observations have taught us that the surface of the earth is never perfectly still. It is always subject to minute tremors or tiny oscillatory movements. At times the tremors become greater, and an earthquake is produced. The oscillations increase to a certain limit and then die down again, or possibly there may be two periods of maximum development before the tremors finally subside. All this is a proof of the instability of the earth's crust. On a much greater scale, earthquakes such as the world experiences at the present time, are but gentle reminders of the huge crustal movements which may take place. Thus taking the history of the Earth we find that at certain periods huge series of earth movements and crustal folding took place, separated by long intervals of comparative quiet. The principal periods of movement were (in Europe) :

1. Pre-Cambrian "Lewisian Movement."
2. End of the Silurian or Siluro-Devonian "Caledonian Movement."
3. End of the Carboniferous or Carbo-Permian "Hercynian Movement."
4. Tertiary "Alpine Movement."

In each case the movements gradually increased to a period of maximum development, and then gradually died down again. The movements which culminated at the end of the Silurian commenced in Cambrian times, and lasted at least to the end of the Devonian.

There is in these great earth-movements "an element of lateral progression, which leads us to picture them in imagination as gigantic waves. In the broad structure of Europe we see the results of four successive earth-waves of the largest order, all advancing in a general sense from the south. The actual belts of folding, as laid down on a map, show sweeping curves, with a certain amount of interlocking. At one place only do three of these belts come together within a relatively narrow space, and it is precisely in this significant situation that the British Isles lie. The unique advantages enjoyed by British geologists result then from the fact that three systems of crust movements, at widely separated epochs, the Lewisian, the Caledonian and the Hercynian [and to a less extent the Alpine also] have all contributed to the building of our country. Moreover, the whole history of Britain can be viewed in relation to these cardinal events, and only when so regarded appears as a coherent sequence." The diagram, *Fig.* 4, shows at a glance the periods of development of these crustal movements.

IV. IGNEOUS PHENOMENA.

Igneous activity almost invariably occurs associated with these great crustal movements. This is illustrated in *Fig.* 4. Moreover, such activity, unaccompanied by earth-movements, is rare. There is also a definite sequence of events in the igneous activity :—

a. **Extrusion** (volcanic activity) and slight intrusion (sills, etc.), during the gathering of crustal stresses and the earlier movements.

b. Intrusion (plutonic activity)—the upwelling of huge masses of igneous rock which do not reach the surface—either at, or shortly after, the climax of the disturbance.

c. Renewed extrusion and slight intrusion (dykes, sills, etc.), during the waning stages of the movement.

The connexion between igneous activity and crustal movements is a fascinating subject which has attracted much attention during recent years. It involves the statement of certain fundamental hypotheses relating to the conditions prevailing in the lower regions of the earth's crust.

The Earth, as a whole, may be considered as comprising four concentric shells (see *Fig.* 1) :—

(i) The Barysphere or Centrosphere occupying the centre. It has a density of about 7, and probably consists of an alloy of iron and nickel—similar in composition to some of the meteorites which fall on the earth's surface. It is assumed to be quite rigid and unyielding.
(ii) The Lithosphere or true crust of the Earth.
(iii) The Hydrosphere—the waters of the ocean.
(iv) The Atmosphere and its upper layers the Stratosphere.

Simple physical considerations tell us that the permanent existence of a great liquid or mainly liquid layer or large reservoir within the earth's crust is impossible. Doubtless extensive tracts of the lower crust are, however, in a semi-liquid state—probably a mass of mineral crystals with interstitial liquid. Such a tract may be termed a Primary Magma-Basin. It possesses some remarkable properties, in particular being very sensitive to unequally distributed stress. If, for any reason, the pressure exerted by the overlying solid crust be lessened, the liquid part of the magma, at least, will tend to move from places of greater pressure to places of less. One can conceive that prolonged denudation over certain areas (continents) and deposition over others (oceans) will in time vary the pressure exerted by the earth's solid crust on the semi-liquid layers below. There is a considerable amount of rigidity in the earth's crust and of inertia to be

overcome, but, sooner or later, this underground movement of magma will take place.

FIG. 1. Diagrammatic Section of a portion of the Earth's Crust, illustrating the hypotheses of Magma Basins and Petrographical Provinces (*L.D.S.*). The black areas represent semi-liquid or recently solidified igneous rocks. The Lithosphere is seen to consist of (a) sedimentary rocks above, passing down into (b) a shell of much folded and metamorphosed rocks. Then (c) below is a shell (marked by crosses) of solid material of the composition of an igneous rock, and which may be considered as a potential magma basin. That is to say, if conditions of pressure, etc., were slightly altered, it would become semi-liquid. 1. A primary Magma Basin. 2 and 2a. Secondary Magma Basins. 3. An intrusive Batholith or Boss. 4[A submarine lava flow. 5 and 5a. Sub-aerial Volcanoes. Other intrusive masses—laccolites and sills are also shown. From A to B is one Petrographical Province, in which rocks of the Spilitic Suite would be expected, from B to C is another, in which rocks of the Pacific Suite would be expected. The rocks under AB would be denser than those under BC.

It is now well established from actual observation that we can recognize more or less clearly defined tracts, within which the igneous rocks, belonging to a given period of igneous activity, present a certain community of petrographical and chemical characters. Such tracts are termed "**Petrographical Provinces.**" With regard to the rocks which may be found in these provinces, they fall into three main series or suites :—

1. **The Atlantic or Alkaline Suite,** in which the rocks are rich in alkalies— Potassium and Sodium. The lavas are mainly basalts, trachytes, and rhyolites, all of alkaline type, with orthoclase and soda-

orthoclase as the dominant felspar. Felspathoids are frequent in the intermediate and basic rocks.

2. **The Pacific or Calcic Suite,** in which the rocks are rich in Calcium. The lavas include basalts, but especially andesites, with some dacites and rhyolites. Orthoclase occurs in the acid and soda-lime plagioclase in the more basic rocks, but felspathoids are absent.
3. **The Spilitic Suite**—chemically not so clearly to be distinguished from the Alkaline Suite—in which soda-rich rocks are dominant, having albite always as the typical felspar, and a rhombic pyroxene as the dark mineral. The most typical lavas are Spilites (Pillow lavas), but more acid types—Keratophyres and "Soda rhyolites" or Quartz Keratophyres occur.

The igneous rocks in one Petrographical Province may vary from acid to ultrabasic, but, as a general rule, they belong to one suite only.

Further, there are some remarkable relations between **Petrographical Provinces, Rock Suites and types of Folding.**

1. **The Atlantic Suite** of rocks is always associated with the Atlantic type of Coast Line, that is to say, with regions characterized by extensive faulting rather than folding.
2. **The Pacific Suite** of rocks is associated with the Pacific type of Coast Line, that is to say, with regions characterized by intense folding.
3. **The Spilitic Suite** of rocks is associated with submarine volcanic action, and with slow submergence to great depths.

So close is the relationship at times that one may have a Province—such as the North British Tertiary Province—characterized by block faulting and rocks of the Atlantic Suite, in which local areas of rocks belonging to the Pacific Suite are also areas of local folding. At different periods of their history, the British Isles have formed part of different petrographical provinces, and this in a manner quite definitely related to the more important series of earth-movements. This relationship is shown in the diagram (*Fig* 4). The inference seems

obvious "that the distribution of crustal stress is a dominant factor in determining the petrographical facies of igneous rock."

The reason for the relationship is not, nowever, easily explained. Returning to the underground movement of magma, certain conclusions must be considered probable :—

1. When there is a transfer of materials on the surface due to the processes of denudation, there is not only a movement of magma underground, but, in order to restore equilibrium, the pressure or weight of rocks in one place must balance the pressure or weight in another place. This is the Principle of Isostasy. Thus the rocks under the ocean must be heavier (denser) than the rocks under mountain ranges.
2. It is reasonable to assume that the whole of the allied rocks in one Petrographical Province have been derived from one magma.
3. From experimental evidence it is known that certain constituents in a rock magma crystallize out before others. If the residual liquid is free to move before crystallization is complete, a natural differentiation is the result.
4. In this way the magma underlying a petrographical province can be regarded as a "Secondary Magma Basin," due to a movement of part of the differentiated magma from the Primary Magma Basin. (See *Fig.* 1.)
5. Similarly the magma in a "Secondary Magma Basin" undergoes progressive differentiation, and thus produces the great variety of chemically allied rock types found in a single province.
6. The order of differentiation is one of increasing alkalinity, and in the main at least, one of increasing acidity or richness in silica.
7. This accounts for the order of intrusion of small masses and also for the (less constant) order of extrusion of lavas, viz. :—
   a. Ultrabasic—rich in Magnesium and Calcium.
   b. Basic.
   c. Intermediate.
   d. Acid.
   e. Ultra-sodic or alkaline.

For details of this subject reference should be made to the works of Dr. A. Harker.[1]

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[1] A Harker, Presidential Address to Section "C" (Geology), *British Association*, Portsmouth, 1911.

A. Harker, Presidential Address to the Geological Society, *Quart. Jour. Geol. Soc.*, vol. lxxiii (1917), pp. lxvii-xcvi.

It must be noted that this section on "Igneous Phenomena" touches summarily on highly controversial matters which belong

V. PHENOMENA OF SEDIMENTATION.

Scarcely less directly than the manifestations of igneous activity, the phenomena of sedimentation depend on orogenic movements.

Indeed, all the great events in connexion with the earth's history tend to be arranged in recurring cycles. Thus we have a Cycle of Crustal Movement—from one period of quietude through a great period of earth movement to another period of quietude. Then there are Cycles of Igneous Activity, both Major Cycles and Minor Cycles, which are closely connected with the Cycles of Crustal Movement. The Major Cycles of Igneous Activity, as we have already seen, correspond in time and position with the Major Cycles of Crustal Movement, whilst the minor events of a period of igneous activity—such as the order of intrusion of different types of rock in one Petrographical Province—tend to recur in Cycles. A similar development of Cycles is apparent in the evolution of life on the globe, and probably also, were our data sufficiently reliable, in the climatic changes which have taken place from time to time.

Still more important in Stratigraphical Geology are Cycles of Denudation and Cycles of Sedimentation.

The Cycle of Denudation.

This Cycle may be considered to commence when a period of earth-movement has caused land to rise above the level of the waters in the surrounding ocean. No sooner does this take place than the forces of sub-aerial denudation come into play. The great tectonic mountains of the newly-formed land are rapidly moulded into different forms, and reduced in size by the agency of rain, frost, wind and insolation. Acted upon together by the eroding and transporting action of running water and moving ice, the land is slowly but surely worn down to the level of the sea (subaerial peneplanation). Another earth-movement may cause the area to rise again, and so end the cycle of denudation, another commencing imme-

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properly to the domain of the Petrologist. But the Stratigrapher cannot afford to ignore these problems if he wishes to gain a comprehensive view of geological history.

diately. On the other hand, after being worn down to sea level, marine denudation may come into play before earth-movements are renewed.

The Cycle of Sedimentation.

Just as with the Cycles of Igneous Activity, both Major and Minor Cycles of Sedimentation may be distinguished. Roughly speaking, the Major Cycles correspond with the great Cycles of Earth Movement, whilst the Minor Cycles correspond with the smaller tremors. Sometimes one period of a Major Cycle—for example, the shallow-water period—may exhibit several Minor Cycles. This is actually the case with the Devono-Carboniferous of Belgium. These two systems there form one great Cycle of Sedimentation, but oscillations have given rise to several Minor Cycles of local importance, as in the Lower Devonian. Minor Cycles may, of course, occur more or less independently during periods of comparative quietude—as in the Eocene of the Anglo-Franco-Belgian Basin.

1. Major Cycle of Sedimentation.

a. Commences by the marine invasion of a land area, giving rise to littoral deposits or a "basal conglomerate" of rolled pebbles of older rocks.

b. As the invasion spreads, shallow-water deposits are laid down over the earlier formed littoral deposits, and pass laterally into shore deposits of later date than those first laid down. Thus it should be noted

(i) that the littoral deposits—"basal conglomerates," etc., are not of the same age throughout;

(ii) that the cycle does not commence at exactly the same time at each point.

These shallow-water deposits consist principally of sands and silts. In the absence of fossils, the presence of glauconite is a very useful test of marine origin. Shallow-water sands may be rippled. Ripples formed by wave-action are symmetrical and thus differ from those formed by air- (low, unsymmetrical) or water-currents (unsymmetrical

with a sharp ridge along one side of the crest). The smaller sand grains are generally angular. One may have also a condition of shallow but clear water, and with very little sediment, in which case shallow-water limestones, especially oolites, may be formed.

c. As the sea spreads and the water deepens, the shallow-water deposits pass upwards into deposits of deeper water—muds, clays and marls.

d. Still deeper water is indicated by certain fine clays, oozes and cherts. Such deposits seem to have been formed very slowly. It is doubtful whether any truly abyssal deposits are to be found in the sedimentary series. This period of deep sea conditions is sometimes termed the Thalassic Period.

e. A reverse movement—one of emergence—then commences. The deep-water sediments pass upwards into shallow-water deposits.

f. Littoral conditions may follow and give rise to a "Gravier d'émersion" (a basal conglomerate is a "Gravier d'immersion").

g. Very probably, however, the fast shallowing sea may give place to lagoonal or estuarine flats, in which clays, sands, etc., with brackish water fossils are formed.

h. As emergence continues such brackish water areas give place to lacustrine areas, or the estuarine deposits may be covered by fluviatile or even æolian deposits. The fluviatile beds are usually current bedded sands, and pale grey or dark lignitiferous clays, with bands of gravel.

i. It is convenient to refer to all deposits, other than marine, as "continental." They never contain original glauconite.

Just as marine deposits may be expected to thicken away from the land,[1] so continental deposits thicken towards the land, and one gets a double wedge-shaped arrangement in section.

k. The Cycle of Sedimentation is brought to a close by the next marine invasion.

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[1] This is only true near the land, in deeper water there is less sediment and accumulation is slow.

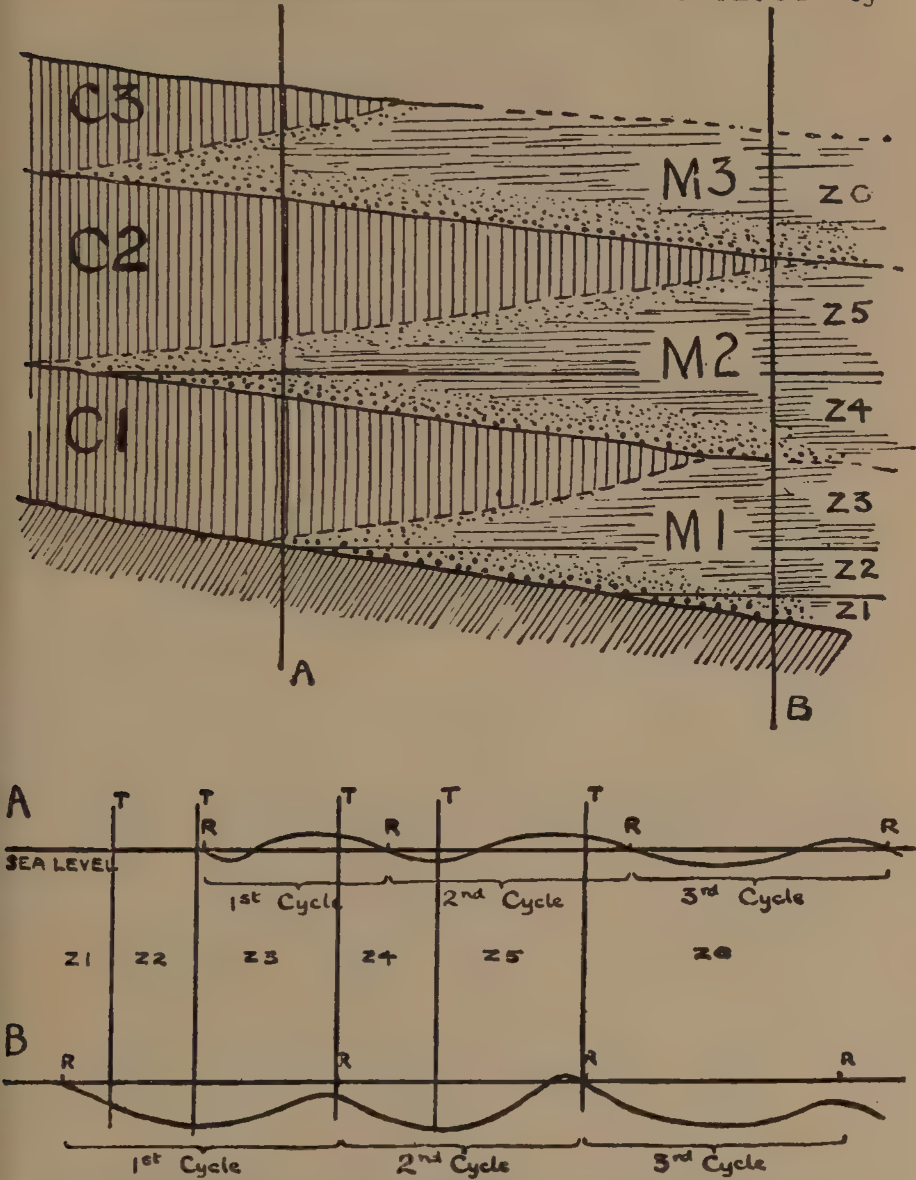

FIG. 2. Diagrammatic representation of three minor cycles of sedimentation. M = marine deposits, showing gradation in coarseness. C = continental deposits. Z = zones, as determined by palæontology. The two graphs show the oscillations of the land surface relative to sea-level at the points A and B. R = position of "ravinements." T = junction planes between zones,

2. Minor Cycle of Sedimentation.

This differs chiefly in the absence of the deep-sea deposits. In fact, a Major Cycle may more simply be defined as commencing with one shallow-water period (marine transgression), and ending with the next great shallow-water period. The stages *g* to *j* above are more characteristic of a minor cycle.

A diagrammatic section of the deposits of three minor cycles is shown in *Fig.* 2. Several interesting features are apparent. The bands marked Z1, Z2, etc., are palæontological zones, and the divisions between them may be taken as representing time planes. It will be noticed—

a. that the cycle commences at different times at different points, *e.g.*, A and B;

b. that the deposits formed at any one time pass laterally from deep-water deposits, through shallow-water deposits into littoral deposits;

c. that when selecting a fossil or fossils for use as zonal indices they should be species which range from comparatively shallow to fairly deep water.

One is almost certain to find a number of species occurring in the littoral deposits throughout, independently of the exact age. A collection of such forms would afford an example of a "facies fauna," of which other examples are cited later.

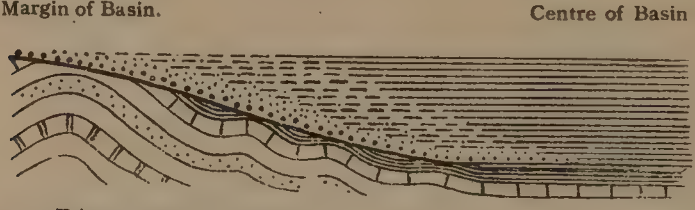

Fig. 3. Diagrammatic Section through the deposits at the base of a Major Cycle of Sedimentation. For explanation see text. (*L.D.S.*)

Fig. 3 is a diagrammatic section through the base of a Major Cycle. It should be noted that the lower series has been folded and denuded along the margin, but that

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Fig. 2 (*continued*).

used as time planes to show the relative time of commencement of each cycle at the points A and B. (*L.D.S.*, reproduced from the *Geol. Mag.*, March, 1921, by permission of the Editor.)

deposition in the centre of the basin has been continuous, and the rocks are there conformable. This illustrates very well the advantage of using a plane of unconformity as the limit between two systems, although it can be traced laterally into a continuous series of deposits. The lower limit of the Devonian in Wales, as well as in the Ardennes and Northern France, behaves exactly in this manner. Thus there is perfect conformity in the centre of the basin (Shropshire), but a gradually increasing break as one travels southward and westward. The same point is illustrated in the previous diagram (*Fig.* 2). The Cycle of Sedimentation, then, forms a very useful basis of classification.

The oscillations of sea-level relative to the surface of the land is shown in the graphs at the base of *Fig.* 2. They are taken for the two points A and B. It will be noticed that cycles can be distinguished in B, although no continental deposits are present.

It should be noted that an extensive unconformity nearly always indicates that the lower series of beds was raised above sea level, *i.e.*, became a land mass, and was subjected to sub-aerial denudation before the second series of beds was deposited. When such an unconformity is traced laterally into a continuous series of marine deposits it is frequently found that, although the bedding of the upper series is parallel to that of the lower, there are signs that the sea, in depositing the upper series, has slightly eroded the top of the lower series. Such an erosion line is termed a "ravinement." There is then usually a thin basal conglomerate. Even when no obvious sign of a break, such as a "ravinement," is present, there may be a sudden change in fauna or a "faunal break." "Non-sequence" is another term applied to faunal breaks in a homogeneous deposit.

The lithological character of a rock, as indicated in one or two cases above, varies according to the conditions under which it was formed. Accordingly, by a careful study of a bed, the conditions under which it was formed can be determined. This is particularly necessary in the case of deposits without fossils. For full particulars reference should be made to works on Physical Geology. Some examples are also given in the text (see page 201). In passing, the following salient features may be noted :—

Æolian Deposits comprise sands, gravels and dust (loess). "Millet seed" sand grains—well rounded and polished even down to minute grains—are characteristic. Polishing and their shape characterize the larger pebbles (dreikanter). The sand ripples, like those formed by currents and tidal action, are unsymmetrical, but are relatively shallower than those formed under water. False bedding is marked and dunes occur (see also under Permian and Trias).

Fluviatile Deposits comprise gravels, sands and clays. The gravels are of partially rounded pebbles, often bleached. The sands are frequently false-bedded and angular grained. Lignitiferous clays, pale plastic pipe-clays and mottled clays are common.

Lacustrine Deposits include clays, silts, marls and limestones. The clays are often mottled; marls and limestones tend to be pale-coloured, and the latter are often hard and cherty.

Estuarine Deposits comprise sands, silts, clays and marls. False-bedding is frequent, but less so than in fluviatile deposits. Sediments are often dark through the presence of much carbonaceous matter.

In all these continental deposits glauconite (except remanié grains) is absent.

One important point should be noted here, and that is the use of the term "**Basin.**" Basins may be distinguished as

1. Original Basins, or Basins of Deposition.
2. Tectonic Basins.

The term is better restricted to the first kind. In this sense a Basin signifies the area in which a group of beds was originally deposited, *i.e.*, a sea or lake, etc. As a result of subsequent earth-movements and denudation the sediments which were deposited over the whole original basin are now only found in the centres of a few synclines. Such remaining areas are tectonic basins. As an example, in Eocene times a single sea covered the South-East of England, the North-East of France and part of Belgium. Doubtless sediments were laid down over the whole of this original Basin or Basin of Deposition. But now the sediments of this old sea are only preserved in four synclinal areas—the tectonic "Basins" of London, Hampshire, Paris and Belgium.

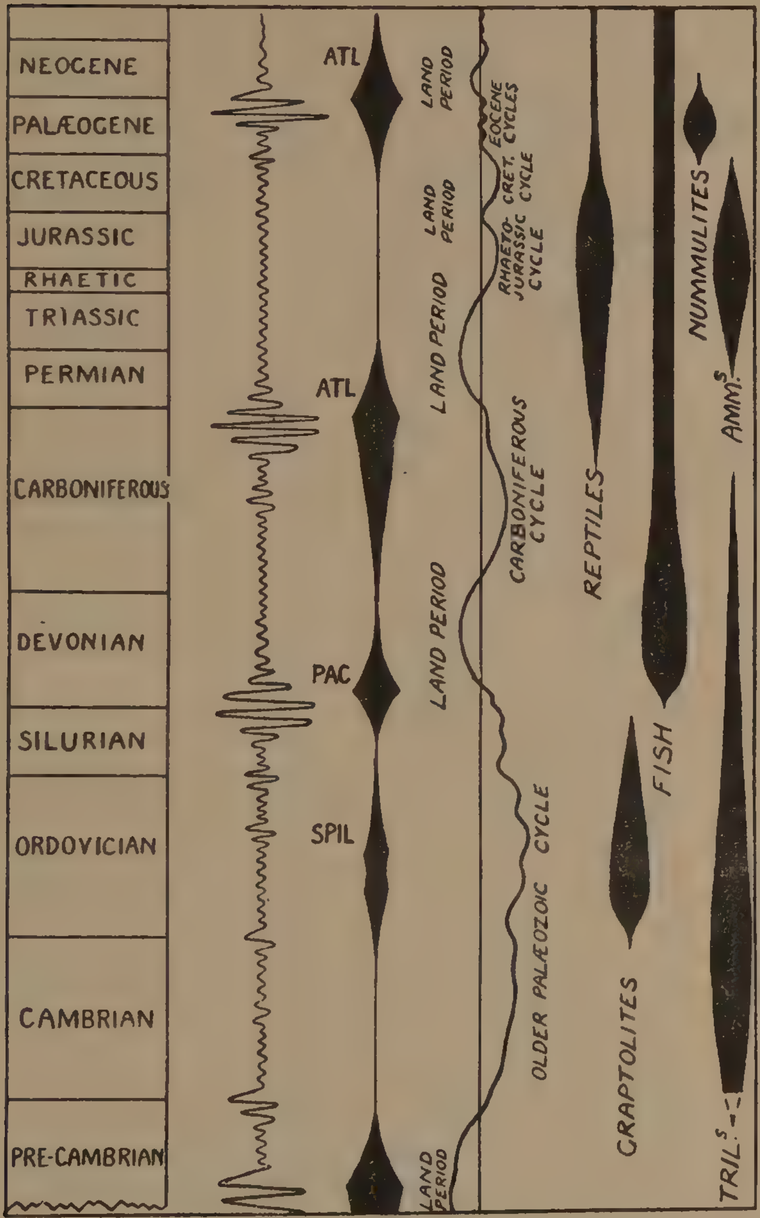

Fig. 4. Diagram showing the Connexion between Cycles of Earth-Movement, Cycles of Igneous Activity, Major Cycles of Sedimentation and Cycles of Organic Evolution. (*L.D.S.*).

VI. PHENOMENA OF CLIMATE.[1]

Sufficient data are not available for any general conclusions to be formed as to the climate of past geological periods.

1. There are probably no deposits known in the whole sedimentary series which are not being or could not be, formed at the present day. It is unnecessary to postulate any very different or abnormal conditions in past ages.
2. The evidence of lithology (*e.g.*, desert sands, etc.) often affords a more reliable guide than does the evidence of palæontology in reconstructing the conditions of past ages. Because corals only grow in warm waters at the present day, that is no reason for presuming that the temperature of the sea in which the Silurian coral reefs grew was higher than that in the British seas at the present day. Because the Coal Measure flora has a superficially tropical aspect it would be wrong to say that the temperature of the whole earth's surface was higher then than now. The whole question may be stated thus: How far is the habitat of groups of animals at the present day indicative of their habitat in past ages?
3. Climatic Zones if they existed in the past must have been differently arranged than at the present day. Palæozoic faunas and floras seem to have been universally distributed over an evenly heated earth's surface.
4. It has been claimed that glacial periods have recurred in cycles during the earth's history. There is certainly ample evidence to prove widespread glacial conditions at various epochs:
   a. Pre-Cambrian (perhaps 2).
   b. Carbo-Permian (Southern Hemisphere).
   c. Pleistocene.

   Other "Ice-Ages" have been claimed to have existed—in the Devonian and Jurassic.

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[1] Since this was written, an interesting book, "The Evolution of Climate," by C. E. P. Brooks, has been published by Messrs. Benn Bros.

5. It has also been claimed that periods of luxuriant vegetation (Carboniferous) separate periods when desert conditions were prevalent (Devonian and Permian), and that the luxuriance was due to a super-abundance of Carbon dioxide in the atmosphere.
6. It should also be noted that a different distribution of temperature and pressure over the earth's surface—the natural consequence of a different arrangement of land and sea—would result in very altered conditions (see page 349).
7. A development of the last idea is the "relief hypothesis" of the causation of ice-ages. This has recently been summarized by Professor Wilhelm Ramsay (*Geol. Mag.*, vol. lxi., 1924, pp. 152-163), who urges that an ice-age occurs after *each* great period of mountain building when not only are the land areas greater than at other times and the mountains loftiest, but also the seas reach their greatest depth. Thus he finds the ice-ages after the pre-Cambrian folding, after the Caledonian (in Devonian times), after the Hercynian (in Permian times) and after the Alpine (in Quaternary times). Compare *Fig.* 19.

VII. PALÆONTOLOGICAL PHENOMENA.

Cycles of Evolution.

One of the difficulties which has to be faced by the modern palæontologist is the question "What is a species?" In the days before the coming of the doctrine of Evolution the idea of the separate creation of species rendered the matter comparatively simple. But now we have learnt that the far more wonderful and ever mysterious force of Creative Evolution controls the life of the Universe. A Creative Force which is continuously at work slowly but surely controlling the minute variations of myriads of creatures seems far more wonderful than a single act of Creation which was finished for ever. Be that as it may, the problem in Palæontology is briefly to decide the limits of variability permissible in a species without the variations becoming so marked as to merit

distinction as separate species. Were the geological record complete and the series of fossils preserved a complete one, the history of each species would be briefly as follows. From the variation of one species, successive changes, minute in themselves but cumulatively important, could be traced until the result differed so much from the parent species that it merited a special designation as a separate species. But the gradual changes do not end there. The new species develops until it reaches the climax of its development or acme, but sooner or later a decline commences and the species either becomes extinct or gives rise to varieties and new species. In other words, " In the course of evolution of species each lineage is believed to attain a more or less prominent ' acme,' when its morphological qualities are relatively static, its distribution commonly wide, and its numerical strength marked."

This rise and fall is seen not only in the evolution of a species, but in the evolution or life of a single individual, and also in the evolution of genera, of families, of super-families and of the great phyla. They all, like species, wax and wane, and are no more. In times past various groups have in turn dominated the earth—the trilobites and graptolites in the Palæozoic, the ammonites in the Mesozoic—and have now left not even one solitary descendant. Other groups remain in diminished numbers—such as the brachiopods, reptiles and great mammals. The waxing and waning of these great groups seems in some way to be connected with the great Cycles of Earth Movement. It is probable that the adverse conditions on an Earth in the turmoil of a great orogenic movement give a stimulus to evolution which is more rapid then than in times of quietude. It must here be remarked that this is strenuously denied by some palæontologists who see here only a coincidence and not a causal relationship. But whichever may be correct, the following points stand out :—

1. The rise of Fish is closely connected with the Siluro-Devonian Earth-Movements.
2. Reptiles rise to importance with the Carbo-Permian Movements and die down with the Cretaceo-Tertiary.
3. Graptolites range in time from the period of the late Cam-

brian Movements to those which brought to an end the Silurian Period.

4. Trilobites disappear with the Carbo-Permian Movements.
5. Ammonites rise to importance after the Carbo-Permian and disappear with the Cretaceo-Tertiary Movements.

This correspondence with the main cycles of earth-movement is shown for some groups in the diagram, *Fig.* 4.

Zone-Fossils or Zonal Indices.

As stated above, the correlation of strata depends ultimately on the fossil-contents of the beds. But not all fossils are suitable for use as indices.

Some species have a very long range in time and but a restricted distribution in space. Others appear at different dates in different localities. A fossil for use as a zonal index should

a. have a restricted vertical range, *i.e.*, a short existence in point of time;
b. be capable of rapid and wide distribution;
c. have a wide horizontal distribution at the time of its acme, and be capable of living under a variety of conditions;
d. be numerically strong;
e. have easily distinguishable characters.

These requirements may be illustrated by means of a distribution diagram (*Fig.* 5).

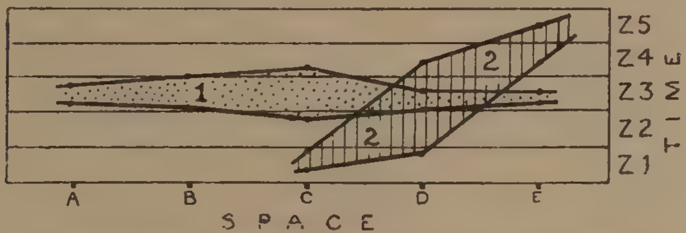

FIG. 5. Distribution diagrams of two species of fossils, 1 and 2. For explanation see text.

A, B, C, D and E are widely separated localities, and the diagram shows the time of appearance and disappearance of a species (1) at each locality. In the same way a species (2) found commonly at C, D and E does not occur in the other localities A and B, and has a large vertical

range. Thus species 1 is suitable as a zonal index to Zone 3 (Z 3), whilst species 2 is not suitable at all.

No fossil attains the ideals for a zonal index—for example, probably no species has an absolutely world-wide distribution at the time of its acme. Hence it is advisable to use several alternative indices for a zone, that is to say, a characteristic faunal assemblage. Care must be taken not to use species which in reality have a long range, but which may appear to have a short one simply because they can only live under special conditions, such conditions only persisting for a short time in any one locality (Species 2, *Fig.* 5, is of this type). As an example, littoral species may appear to die out when deeper-water conditions come on, but reappear with the return of littoral conditions. In other words, they simply migrate away with the shore-line. The question of "facies fossils" is often a difficult one. The Muschelkalk of Germany (Middle Trias) was laid down in an enclosed arm of the sea. The whole fauna is specialized, and appears to die out before the overlying sandy beds were deposited. But it reappears when suitable conditions returned at a later date. In the correlation of two different facies—for example, the deep-sea graptolitic and the shallow-water shelly facies of the Ordovician—it is necessary, in addition to zonal species for each facies either to find a transitional area between the two facies, or to use species common to both facies.

The Correlation of Strata by Zonal Indices.

As already stated above (p. 2) the law of strata identified by fossils is a fundamental one and one on which the whole study of historical geology is based. Provided care is taken, as indicated in the last section, in the selection of species to be used as zone-fossils or zonal indices and more especially when a *whole assemblage* can be used the correlation of strata, even over a very wide area, rests on a sure basis.

But of recent years palæontologists have tended to divide the geological column into smaller and smaller divisions. The sequence of Jurassic faunas in particular has been investigated in some detail, with the result that

a very large number of "hemeræ" have been distinguished. The work is associated especially with the name of the late S. S. Buckman. Buckman refers to the strata formed during a hemera as a "zone," and so his very numerous zones replace the broader zones of other palæontologists. At present a severe battle is being waged as to the validity and value of Buckman's hemeræ or zones. It is impossible to summarize the diverse views here, but the reader is referred to the following four papers which give a fairly clear idea of the position.

(*a*) An excellent summary of the Buckman conception was given by Professor A. E. Trueman, "Some Theoretical Aspects of Correlation" (*Proc. Geol. Assoc.*, vol. xxxiv., 1923, pp. 193-206).

(*b*) A reply to the latter paper, attempting to define some of the factors of the environment which must of necessity have limited the spread of organisms in the past as at the present, was given by L. D. Stamp, "Some Practical Aspects of Correlation—a Criticism" (*Proc. Geol. Assoc.*, vol. xxxvi., 1925, pp. 11-27).

(*c*) A spirited defence of Buckman and a reply to some of the points in the last paper was given by one of our leading palæontologists, Professor A. Morley Davies, in his Presidential Address to the Geologists' Association—"The Geological Life-Work of Sydney Savory Buckman" (*Proc. Geol. Assoc.*, vol. xli., 1930, pp. 221-240).

(*d*) On the other hand another of our leading palæontologists, Dr. L. F. Spath, once a great disciple of Buckman, has now expressed himself in no uncertain terms by saying that the "value of these local subzones for purposes of an ideal time-scale is nil" and that facts which he now quotes "show that Buckman's hemeral 'chronology' is useless" (see "On the Contemporaneity of Certain Ammonite Beds in England and France," *Geol. Mag.*, vol. lxviii., 1931, pp. 182-187).

The importance of ecological factors in the plant life of the Carboniferous will be discussed in the chapter dealing with that System.

In conclusion, the following terms should be noted: two deposits formed at the same time are said to be synchronous. Horizon is a term applied to a time plane, *i.e.*, deposits which are said to be on the same horizon in two different countries were formed at the same time. Deposits in widely separated areas, containing the same assemblage of fossils, are said to be "homotaxial."

The latter is a cautious term in that it does not imply contemporaneity. Where a faunal break seems to indicate a period of non-deposition which is not, however, apparent from the lithology of the rocks a "non-sequence" is said to occur.

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IGNEOUS :—A. Harker, The Natural History of Igneous Rocks, *Methuen*, 1909, and papers quoted above.

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CHAPTER II.

STRATIGRAPHICAL PALÆONTOLOGY.

The great divisions of Geological Time—the Palæozoic, Mesozoic and Kainozoic Eras — have been founded, as their name implies, on a study of the contemporary animals and plants. The definition and identification of the smallest division of geological time — a hemera—depends entirely on a careful study of the creatures living during that time. Thus it is seen that a Stratigrapher cannot go far without the help of Palæontology. We have already pointed out that one species of fossil grades into another, and it is, for the most part, purely the work of the specialist in palæontology to undertake the specific identification of fossils. There are two errors into which the Stratigrapher is very prone to fall. One is to rush to conclusions, and to give a fossil a definite name without proper care. For example, he may recognise a fossil as *Spirifer*, and (unfortunately) remembers that *Spirifer striatus* is a very common species from the Carboniferous Limestone. He immediately calls the specimen *Sp. striatus* when it is possibly a superficially similar Devonian species. Even after a careful comparison with a figure of an undoubted *Sp. striatus* it would often be better to label the specimen as *Spirifer* cf. *striatus*. The other is practically to ignore palæontology. How often does one meet a so-called (usually self-styled) " practical field geologist " who cannot be bothered with fossils! The frequent result is that he confuses two lithologically similar beds and misinterprets the whole succession.

There are three golden rules for stratigraphers who wish to become successful field geologists.

a. To know and to know thoroughly the general characteristics of the faunas of each period and of the major subdivisions.

b. Not to trespass into the domain of the palæontological specialist by naming fossils (in full) at sight. It may sound learned to identify a crushed graptolite in the field as *Glyptograptus teretiusculus* var. *siccatus*, but it would be wiser and safer to refer to it as a crushed Diplograptid.

c. To cultivate an observant eye for fossils. It is often possible to identify a stratigraphical horizon by certain fossils, even though one cannot give them a name. They may not even have names. It is often possible to say definitely that one is dealing with, for example, a freshwater deposit, by the general character of the fossils, without naming a single one.

On broad palæontological lines it is possible to distinguish *four great faunal epochs* :—

I. *The Older Palæozoic* (*Proterozoic*) comprising the Cambrian, Ordovician and Silurian Periods.

II. *The Younger Palæozoic* (*Deuterozoic*) comprising the Devonian, Carboniferous and Permian Periods.

III. *The Mesozoic.*

IV. *The Kainozoic*, including Recent Times.

The characters of the faunas of these great epochs, as well as of the separate periods, have been detailed by Professor H. L. Hawkins,[1] and have been summarized very briefly by Professor A. Morley Davies.[2] A fuller treatment was later given by Professor E. Neaverson.[3] The subject will, accordingly, be passed over rapidly here.

I. *THE OLDER PALÆOZOIC FAUNAS.*

Representatives of most of the great groups of Invertebrate Animals are found in Cambrian strata. Even in early Cambrian times many of them—for example, the Trilobites—had reached a comparatively advanced stage of evolution. Hence we presume that their ancestors must have existed in Pre-Cambrian times. The actual

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[1] H. L. Hawkins, "Invertebrate Palæontology,' 1920.
[2] A. Morley Davies, "An Introduction of Palæontology," 1920
[3] E. Neaverson, "Stratigraphical Palæontology," 1928.

fossil remains of the Pre-Cambrian Period are, in England, restricted to worm casts and burrows, and a few structures of doubtfully organic origin. The famous "*Eozoon*" of Canadian Pre-Cambrian rocks has been shown to be an inorganic structure. Although many of the Cambrian fossils exhibit a high state of development, it must be noted that many of them have hard parts which tend to be chitinous rather than calcareous or siliceous. A thin chitinous exoskeleton would not be preserved except in very exceptional circumstances, and it is reasonable to presume that the Pre-Cambrian seas were swarming with soft-bodied primitive animals of all kinds, but which have left no trace. Since all animals, directly or indirectly, depend on plants, which alone can assimilate inorganic food substances, for their existence, we must presume also that plant-life existed in Pre-Cambrian times. Curiously enough undoubted plant-remains are practically absent in Lower Palæozoic strata.

The main characters of the Lower Palæozoic Faunas may be summarized as follows:—

a. Plants are practically absent.

b. Vertebrata are absent. It is an Age of Invertebrates. [The dominant invertebrates were Trilobites, Brachiopods and Graptolites (latter are entirely restricted to the Lower Palæozoic).]

c. Arthropoda (jointed invertebrates). Trilobites are abundant. On the whole they were rather shallow-water creatures, and are often used as zonal fossils in shallow water or "shelly" facies. There are some, however, which are apparently adapted for deep-sea life; they have either very large eyes or no eyes at all. Certain little true Crustacea are common, and some, like *Beyrichia*, flourished exceedingly in special circumstances. Insects are unknown in the Lower Palæozoic. Eurypterids become important in the highest beds.

d. Mollusca. Compared with later periods Gastropods and Lamellibranchs are not very important. They are for the most part shallow-water creatures, and do not afford a very ready indication of age. Among Cephalopods—Molluscs with a chambered shell—straight or slightly curved Nautiloids are important, especially *Orthoceras*, but Ammonoids are completely absent.

e. Brachiopoda. The horny-shelled representatives are especially characteristic, and, apart from such forms as *Lingula,* which have persisted to the present day, are almost restricted to the Lower Palæozoic. Calcareous brachiopods become especially important in the middle and higher parts (Ordovician and Silurian), notably *Orthis.*

f. Echinodermata. The primitive cystids (almost restricted to the Lower Palæozoic) and the crinoids are important. Blastoids and Echinoids just appear, but are rare.

g. Cœlenterata. The Graptolites are extremely important,[1] they are mostly adapted for life in deep or still waters (shaly facies). Corals are represented by the Rugose and Tabulate types.

h. Porifera. Sponges are not important unless the curious Cambrian group, the Archæocyathineæ, can be referred to the Porifera.

i. Protozoa. Despite the relative simplicity of structure of the Radiolaria and Foraminifera they are not important in early Palæozoic strata. Probably the early forms had chitinous skeletons.

II. THE NEWER PALÆOZOIC FAUNAS.

The age of **Fishes** and **Fern-like Land-Plants (Pteridosperms),** associated with Goniatites, Spiriferid Brachiopods, and Rugose Corals.

a. Plants. The seed-bearing but fern-like Pteridosperms are especially important in the middle of the period.

b. Vertebrata. The dawn of the Devonian is the dawn of an Age of Fishes. The only other vertebrates are rare Amphibians and a few reptiles in the higher part.

c. Arthropoda. This period marks the fall and extinction of the Trilobites and Eurypterids, but the rise of the Insects.

d. Mollusca. The Upper Palæozoic is an age of Goniatites—straight or coiled Ammonoids (the

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[1] On the great groups which characterize different periods, see p. 84.

former only to be distinguished from the straight Nautiloids by the ventral position of the siphuncle) with simple suture lines. The Nautiloids show a steady decline.

e. *Brachiopoda.* Great development of Productids and Spiriferids.

f. *Echinodermata.* An age of Blastoids, associated with primitive echinoids with more than two columns of interambulacral plates.

g. *Cœlenterata.* Graptolites are extinct; Rugose corals are very important; Tabulate corals and Stromatoporoids occur especially in the lower part of the Upper Palæozoic.

h. *Protozoa.* Both Radiolaria and Foraminifera become more important than in the Lower Palæozoic.

III. THE MESOZOIC FAUNAS.

The Mesozoic is an Age of **Reptiles** and **Ammonites,** associated with Belemnites, Rhynchonellid and Terebratulid Brachiopods, true Crinoids and true Corals.

a. *Plants.* An age of Cycads and Monocotyledons. also Conifers and Ferns, but from the point of view of the floras the Tertiary era begins before the end of the Cretaceous, as the group of the Dicotyledons then becomes abundant.

b. *Vertebrata.* Reptiles are the great group; they peopled the air, the land and the water, and reached their acme rather later than the middle of the period. Mammals and Birds appear, but are comparatively insignificant in size and numbers.

c. *Arthropoda* are neither very distinctive nor important.

d. *Mollusca.* Lamellibranchs are remarkable for the great development of *Ostrea* and *Trigonia,* Gastropods for *Pleurotomaria* and *Nerinæa.* Absolutely characteristic of the Mesozoic are the Ammonites and Belemnites, the former of paramount importance as zone-fossils.

e. *Brachiopoda.* Apart from a few survivals of Palæozoic genera and a few long-range forms like *Lingula,* nearly all the abundant Mesozoic brachiopods belong to the "genera" *Terebratula, Terebratella* and *Rhynchonella.*

f. *Echinodermata.* Cystids and Blastoids are extinct; Crinoids become less and less important. Echinoids are abundant, both regular and irregular forms.

g. *Cœlenterata.* True corals are important when conditions were suitable (clear water).

h. *Porifera.* Sponge spicules are often important as rock formers.

i. *Protozoa.* Foraminifera important (especially in the chalk).

IV. THE KAINOZOIC FAUNAS.

The Age of **Mammals** and **Birds,** of great **Foraminifera,** and of **Angiospermous plants.** Recent times (Quaternary) cannot be separated faunistically from the Kainozoic.

a. *Plants.* Modern types of Dicotyledons and Monocotyledons, including Palms and similar plants, which now only flourish in tropical or sub-tropical regions.

b. *Vertebrata.* The Reptiles of the Mesozoic are practically extinct, and the long dormant groups of Placental Mammals and Birds become dominant.

c. *Arthropoda.* Include those common at the present day.

d. *Mollusca.* Gastropods and Lamellibranchs have a definitely modern facies, and most of the genera are still living. Cephalopods have become almost extinct. Ammonites and Belemnites have gone entirely.

e. *Brachiopoda.* Rare.

f. *Echinodermata.* Crinoids rare; echinoids are common in warmer waters, or where water was clear —not in the English regions.

g *Cœlenterata.* Reef-building madreporaria flourished in tropical waters, as at the present day.

h. *Porifera.* Sponges are not important.

i. *Protozoa.* Foraminifera are of great importance, the giant *Nummulites* in the earlier part, and *Globigerina* at the present day. The former are important zone fossils. Radiolaria are often common.

CHAPTER III.

THE MORPHOLOGY OF THE BRITISH ISLES.

Before commencing a study of the Stratigraphy and Palæogeography of the British Isles, it is very useful to have a general knowledge of the natural regions of the country.

A. SCOTLAND falls naturally into three regions:

1. THE HIGHLANDS.
2. THE MIDLAND VALLEY.
3. THE SOUTHERN UPLANDS.

1. The Highlands of Scotland are sharply limited on the south by the Great Highland Boundary Fault, which runs from the mouth of the Clyde in the south-west to the neighbourhood of Stonehaven in the north-east. They consist in the main of a massif of crystalline rocks, probably all of Archæan age. The structure of the two principal divisions—the North-West and the Central Highlands—is explained in the account of the movements which produced them (see page 100). The "grain"—that is the dominant strike of the country—is from S.W. to N.E., though along the west coast the direction of the long fiords has been influenced by major lines of weakness in different directions. Along the east coast are large areas covered by Old Red Sandstone and smaller areas of Jurassic rocks. Along the north-western margin is a belt of Cambrian and Pre-Cambrian Sediments, whilst along the west coast—on the islands of Mull, Skye, Eigg, etc., vast eruptions of Tertiary Volcanic Rocks cover the older strata. Speaking generally, the drainage system either follows the grain of the country—S.W. to N.E. or vice-versa—or the general slope of the peneplaned surface towards the east. The valleys have been extensively modified by glaciation.

2. The Midland Valley is a great trough or rift valley let down between two great faults or series of faults running from S.W. to N.E. These are the High-

FIG. 6. Morphological Map of the British Isles. Vertical lines, Pre-Cambrian; oblique lines, Older Palæozoic; horizontal lines, Newer Palæozoic; solid black, Exposed Coalfields; T. Triassic Plain of the Midlands; unmarked, Mesozoic; dotted, Tertiary. It must be remembered that these are only broad divisions, and not strictly accurate, thus there are large areas of Old Red Sandstone, etc., in the part of Scotland indicated as Pre-Cambrian. (*L.D.S.*)

land Boundary Fault to the north and the Southern Boundary Fault to the south. The Valley is essentially a disturbed geosynclinal of Upper Palæozoic Rocks, the Old Red Sandstone occurring along the margins, the Carboniferous in the centre. The presence of contemporary lavas and of infertile hard rocks, especially in the Old Red Sandstone, account for the hilly floor of the valley. It is agriculturally and industrially the most important part of Scotland.

3. The Southern Uplands comprise an anticlinorium of Lower Palæozoic Rocks, for the most part giving rise to stretches of barren moorland with some agricultural regions.

B. ENGLAND AND WALES can be divided into—

1. THE LAKE DISTRICT, with the ISLE OF MAN. } Palæozoic.
2. PENNINES and North of England. } Palæozoic.
3. THE WELSH MASSIF. } Palæozoic.
4. DEVON AND CORNWALL.
5. THE POST-PALÆOZOIC REGION OF LOWLAND OR SOUTH-EASTERN ENGLAND.

1. The Lake District consists of a central mountainous area of slates and volcanic rocks of Lower Palæozoic age, almost surrounded by a ring of lowlands consisting of younger rocks. It has a well marked radial drainage, almost independent of the structure of the massif. The Isle of Man also consists mainly of Palæozoic rocks.

2. The Pennines consist very largely of Carboniferous rocks, and stretch from the border of Scotland southwards as far as Derbyshire. The central ridge (Pennines proper), or "Backbone of England," consists of wild moorlands of grit, with limestone areas characterized by caverns. On either side of the central ridge are the great coalfields of Northern England. The drainage is mainly east and west from the central ridge, but the Derwent, flowing eastwards, was dammed up by ice during the Glacial Period, and forced to cut a gorge southwards.

3. The Welsh Massif, comprising Wales and the Border counties, is a great region of Palæozoic rocks. The older rocks in the north have a S.W.-N.E. (Caledonian) trend impressed on them partly during the Siluro-Devonian movements and partly later; the newer rocks in the south—including the South Wales Coalfield—have an east to west (Hercynian) trend, whilst a north to south alignment is developed along the eastern border of the massif (see page 173). The drainage in the north tends to be radial, and, though superimposed, has become adapted to the main grain of the country. The Severn, which should obviously flow into the Dee, has been deflected southwards by glacial interference. In the south the drainage cuts right across the folding, and flows from north to south, but the valleys are largely determined by faults. The greater part of Wales is mountainous, or consists of barren moorlands. Even the busy industrial centres of South Wales are restricted to the valleys, and are separated by stretches of wild moor. The Old Red Sandstone marls of the Border Counties afford some of the most fertile regions.

4. Devon and Cornwall consist mainly of a complicated synclinorium of Devonian and Carboniferous rocks, with great intrusive masses of granite.

5. The South-East and Midlands of England—roughly to the south-east of a line from the Devon-Dorset boundary to Northern Yorkshire — comprises the great agricultural regions of England. The Triassic plain of the Midlands, however, lies to the north-west of this line and the beds wrap round the Midland Coalfields (see *Fig.* 6). The whole area of S.E. England consists of a blanket of Mesozoic Rocks resting on an eroded surface of Palæozoic rocks called the Palæozoic Platform. These old rocks sometimes — towards the north-west—appear at the surface as large inliers, such as the Mendip Hills, South Staffordshire Coalfield, Charnwood Forest, etc. In two areas, resting on Mesozoic rocks, Tertiary Strata are important:—

a. London "Basin" and East Anglia.
b. Hampshire "Basin."

The Mesozoic region consists of a series of escarpments facing north-westwards, with their dip-slopes towards London. In Kent, Surrey and Sussex is the oval Weald—a large anticlinal area. The drainage is mainly consequent, *i.e.*, with the dip of the beds, but numerous examples of river-capture are to be seen. In one case at least after the consequent stream had cut down into Palæozoic strata a reversal of drainage took place, giving rise to the Bristol Avon. The River-system of the Weald affords classical examples of capture by subsequent tributaries of one stream beheading neighbouring consequent streams. The South-East of England is mainly agricultural, and it is the Mesozoic and Tertiary rocks which give rise to that " close " type of scenery—little woods, fields and villages mixed in endless variety—which is so eminently " English."

C. IRELAND.

The surface of Ireland is shaped like a saucer. It consists of a Central Plain surrounded by a ring of mountains. Practically all the solid rocks are Palæozoic. The Plain has a floor of Carboniferous Limestone, but is largely covered by glacial drift and recent peat. It is interrupted at intervals by hills, due to anticlines of Old Red Sandstone or the remnants of synclines of Coal Measure Sandstones.

Of the ring of mountains—

a. those in the north-west are a continuation of the Highlands of Scotland, and have the same trend;

b. those in the north-east are a continuation of the Southern Uplands, but the Tertiary Basalt Plateau of Antrim is linked with the Tertiary Igneous Rocks of the west coast of Scotland;

c. those in the south-east are a continuation of the Welsh Massif (northern part);

d. those in the south-west are a continuation of the South Wales Hercynian folds, but these have a west-south-west trend, and run into the sea as long peninsulas separated by " rias."

CHAPTER IV.

THE PRE-CAMBRIAN SYSTEM.

Under the non-committal term "Pre-Cambrian" is grouped a heterogeneous series of rocks whose only title to be considered together lies in the fact that they are older than the fossiliferous rocks of the Cambrian System. The Pre-Cambrian Era is also known as the Azoic or Eozoic. Both these terms are bad; the first presupposes that life did not then exist, the second that the era marks the dawn of life. The term Archean is also used, but sometimes also in a more restricted sense.

A **two-fold division** of Pre-Cambrian Rocks is possible—

1. A series of highly metamorphosed rocks—crystalline schists and gneisses.
2. Sedimentary rocks, generally resting with a well-marked unconformity on the crystalline series. These rocks only differ from the sedimentary rocks of later systems in the absence of fossils.

The Crystalline Rocks,[1] formerly collectively known as the "Fundamental Complex," attain an enormous thickness, and consist of highly metamorphosed rocks. They seem to consist largely of altered plutonic rocks—gneissose granites, etc.—but may include also altered sediments. The idea that these rocks represented the original crust of the earth for long held sway, but now the opinion of those who have studied them tends more to regard them as highly altered series of sediments and igneous intrusions. This is certainly the case with the great area known as the Canadian Shield. In most cases, however, although the areas of Pre-Cambrian crystalline rocks are not portions of the original crust of the earth, many of them have been areas of very great

[1] The name Archean is often restricted to this division.

FIG. 7. The main structural divisions of the world. a1-a9 plateaus of ancient rocks; b1-b3 lowlands of ancient rocks; c1-9 lowlands of sedimentary rocks; black, main mountain belt.

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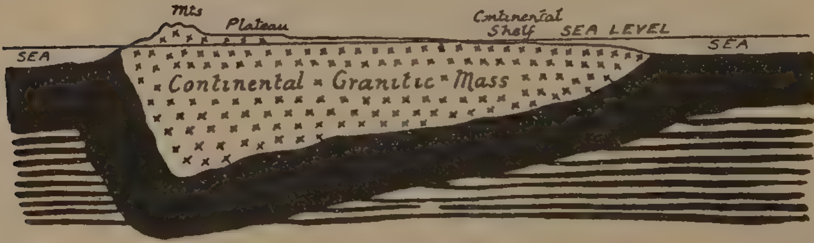

FIG. 7a. Diagram of a continental granitic mass floating on a substratum of basaltic material (in black). Below the latter there may be another layer—the peridotic.

Reproduced from Stamp's "Asia," by permission of Methuen and Co., Ltd.

stability since very early times. Some remain as large plateaus and are numbered a1 to a9 on *Fig.* 7; others have been worn down almost to sea level and are numbered b1 to b3 on *Fig.* 7. In other cases, notably in European Russia, the ancient rocks have formed a stable block which has, however, undergone slow movements of elevation and depression so that younger sediments cover the surface. But the main areas of Pre-Cambrian rocks have not been submerged since Cambrian times, or, if they have (as in European Russia) the overlying sediments are quite unaltered and not folded. It will be noticed that the British Isles do not form part of one of these areas, and our Pre-Cambrian and later rocks have been much folded and faulted.

In recent years, what is known as the Wegener hypothesis has, with various modifications, attracted much attention. It conceives of the great continental masses as consisting of lighter rocks resting on a heavier substratum and capable of movement relative to one another. Thus the ancient pre-Cambrian blocks can be regarded as having originally have formed part of one mass which has since split up and the fragments drifted apart. Reference should be made to the now extensive literature on the subject. (See *Fig.* 7a.) Much work has been done on the dating of Archean rocks by their radioactive minerals and this has revealed the vast eons of time involved.

PRE-CAMBRIAN IN THE BRITISH ISLES.

A. Scotland.

The whole of Scotland north of the Highland Boundary Fault may be regarded as a massif of Pre-Cambrian crystalline rocks, penetrated by numerous intrusive masses largely of Pre-Cambrian age also. The massif is partly covered by areas of Old Red Sandstone, patches of Mesozoic strata and sheets of Tertiary lavas. A strip of Cambrian rocks occurs in the north-west, and also along the southern boundary.

The Pre-Cambrian Rocks of Scotland may be divided into—

4. Torridonian, sedimentary series.
3. Dalradian }
2. Moinian } crystalline series.
1. Lewisian }

FIG. 8. Diagrammatic Section across the Highlands of Scotland from North-West to South-East. 1, Lewisian. 2, Loch Maree Series. 3, Moinian. 4, Dalradian. 5, Torridonian. 6, Cambrian. 7, ?Cambrian. 8, Intrusion of "Newer Granite" (Siluro-Devonian). 9, Old Red Sandstone. TT, Moine Thrust Plane. FF, Highland Boundary Faults. OD, Sea Level. (*L.D.S.*)

The relation of these groups to one another may best be expressed by means of a diagrammatic section (*Fig.* 8) across the Highlands from north-west to south-east (see also the chapter on the Siluro-Devonian Folding).[1]

It will be noticed that—

a. the Torridonian rests unconformably on the Lewisian;

b. the fossiliferous Cambrian covers both the Torridonian and the Lewisian unconformably, and there is thus no doubt as to their Pre-Cambrian age;

c. the Moinian is thrust over the Cambrian, but is not covered by rocks earlier than Old Red Sandstone. Its Pre-Cambrian age is, however, proved by the occurrence in the Torridonian of pebbles of Moinian rocks;

d. the relation between the Moinian and the Dalradian is still uncertain.

1. Lewisian. A group of coarse gneisses and schists, forming the foundation of north-western Scotland and the greater part of the Hebrides (hence the name Hebridean).

a. The gneisses have the mineralogical character of

[1] See "Scotland: The Northern Highlands," 2nd Ed. (British Regional Geology), *H.M.S.O.*, 1948, with a summary of the classic memoir on the North-West Highlands, by B. N. Peach and J. Horne, 1907.

altered plutonic rocks. In places lenticular masses of normal plutonic rocks—granites, etc.—occur and seem to pass laterally into the gneisses. They vary in composition from ultrabasic to acid. The dominant type is a pyroxene gneiss, but hornblende-biotite- and biotite-muscovite-gneisses occur.

b. The schists are also probably altered igneous rocks, but from their composition might be metamorphosed sediments (arkose).

c. The complex of gneisses and schists is riddled with a great series of basic and ultra-basic dykes, mostly dolerites. They are nearly all Pre-Torridonian, and much altered where they are in the region of shear-planes.

d. In certain areas, notably round Loch Maree, and apparently occupying a syncline in the gneisses, are rocks which are clearly altered sediments—including marbles and cherts.

e. The Lewisian group has been affected by Pre-Torridonian folding movements, and is also crossed by a series of shear-planes, running for the most part W.N.W. to E.S.E. (*i.e.*, parallel to the majority of the basic dykes), which have produced bands of intense foliation.

2-3. Moinian and Dalradian, sometimes known collectively as the Eastern Schists.

a. The " Moinian " occurs as a broad belt on either side of the Great Glen (which W. Q. Kennedy has shown marks a great fault with lateral movement) ; the " Dalradian " as a broad belt along the southern border of the Highlands.

b. The Moinian or Moine Schists consist of siliceous schists or gneisses which weather into flag-like slabs. The most typical member is a granulitic quartz-felspar rock, with grains of almost equal size of quartz and alkali-felspar. In the neighbourhood of thrust planes they have been broken down into mylonites. Garnetiferous mica-schists also occur.

c. The Dalradian or Grampian comprises a complex series of schists, gneisses, quartzitic grits and crystalline limestones. A definite succession has

been made out right across Scotland, but it is probable that it is not a simple succession but complicated by overfolding and faulting. Even if regarded as a simple succession it is still uncertain which way up it should be read. In the south-west, where the group has been specially studied, it would seem that numerous extensive thrust plains exist.[1]

d. Very great difference of opinion exists as to the relation between the Moinian and Dalradian.

(i) Professor J. W. Gregory[2] regards the observed succession in the Dalradian as a true one, and considers that the Dalradian sediments were deposited unconformably upon the southern flanks of a land consisting of Lewisian and Moinian rocks.

(ii) Some of the Geological Survey officers consider the Dalradian are older than the Moinian, and that the apparent superposition is explained by great overfolds.

(iii) Mr. G. Barrow explains the less altered condition of the Dalradian by considering the Scottish Highlands as a great metamorphic aureole in which the metamorphism is most intense in the centre, and the beds become less crystalline to the north-west and the south-east. (See page 106.)

e. The relation of the Moinian to the Lewisian is also disputed.

(i) Evidence near Glenelg and in Ross-shire

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[1] E. B. Bailey, "The Structure of the South-West Highlands of Scotland," *Quart. Jour. Geol. Soc.*, vol. lxxviii., 1922, especially pp. 86-93 and 95-108. Further evidence on how to read the order of the sequence was detailed by T. Vogt and accepted by E. B. Bailey (see *Geol. Mag.*, vol. lxvii., 1930, pp 68-91). Professor Bailey's maps have been reproduced below, pp. 104, 105. A very different interpretation has been put forward by J. F. N. Green ("The South-West Highland Sequence," *Quart. Jour. Geol. Soc.*, vol. lxxxvii., 1931, pp. 513-550), who considers that the dominant structure is one of short isoclinal folds.

[2] Shortly before his death by drowning in Peru, Professor Gregory summarized his views in a book entitled "Dalradian Geology" (*Methuen*, 1932), but he is almost alone in his interpretation of the sequence. See "The Grampian Highlands," 2nd Ed. (British Regional Geology), *H.M.S.O.*, 1948.

seems to show that the Moinian rests unconformably on the Lewisian, and has a conglomerate at the base.

(ii) The Moinian may be of the same age as the schists round Loch Maree, *i.e.*, roughly of the same age as the Lewisian complex.

(iii) It has been suggested that the Moinian rocks are altered Torridonian.

f. Both the Moinian and Dalradian are penetrated by large plutonic masses — especially granites, diorites, etc. At least a considerable number appear to be Pre-Cambrian, and are much altered, but many belong to the Siluro-Devonian Cycle of Igneous activity.

4. Torridonian.

Like the Old Red Sandstone of later date, the Torridonian sediments were accumulated in mountain-girt desert-basins. The movements which foliated the Lewisian complex did not affect the Torridonian, hence we can picture the mountains of Lewisian gneiss, very much as we know them at the present day, towering over the Torridonian deserts. The sediments fill up the hollows in the old land surface; naturally the lowest are coarse breccias — largely consisting of fragments of Lewisian gneiss, but including also pebbles of volcanic rocks (of unknown origin, but much resembling the Uriconian of England)—and, more locally, conglomerates. The bulk of the Torridonian consists of coarse sandstone, which has abundant fresh felspar grains—especially microcline. This shows that the sediment cannot have been derived directly from any of the neighbouring gneisses, which are poor in that mineral. The Torridonian, on the whole, is coarser in the north, some of the grains are polished in a manner characteristic of æolian deposits, other beds more closely resemble torrential deposits. The included pebbles are often faceted by wind action (dreikanter). The maximum thickness of the Torridonian is over 20,000 feet, and it is divided into three series :—

3. Aultbea Series : sandstones, with shales.
2. Applecross Series : coarse red arkose.

1. Diabaig Group: sandstones, with shales.

The "shales" have surfaces marked with rain-pittings and sun cracks.

The whole of the Torridonian deposits were accumulated very rapidly, and the freshness of the felspar is considered to indicate tropical conditions.

The structure of the Highlands of Scotland is largely the result of the Caledonian (Siluro-Devonian) Movements, and further details will be found in the account of those movements (see page 100).

B. England and Wales.

The Pre-Cambrian rocks of England and Wales are exposed in a number of isolated inliers rising from beneath newer rocks. The correlation of these different areas will always be a matter of great difficulty, and must depend on a careful study of lithological characters.

The usual two-fold division is possible, viz. :—

1. Crystalline Series.
2. Sedimentary Series.

In addition, a third group may be added

3. Extrusive igneous rocks, chiefly lavas and ashes. Some plutonic masses appear to be closely connected.

The areas of Pre-Cambrian rocks are :—

1. South of England (Lizard District and Start Point).
2. South Wales (Pembrokeshire).
3. North Wales (Carnarvonshire and Anglesey).
4. Shropshire.
5. The Midlands (Malvern, Lickey Hills, Nuneaton, and Charnwood Forest).
6. Yorkshire (Ingleton)?

1. South of England.

Lizard District. This district affords a fine example of a plutonic complex. The whole is regarded as Pre-Cambrian in age.

a. The country-rocks are mica-schists, granulites and quartzites (metamorphosed sediments) with hornblende-schists (metamorphosed basic lavas or sills and ashes). The oldest rock of all is probably a foliated gneiss off the south-west coast.

b. The earliest plutonic intrusion is, as usual, the ultra-basic—a great mass of serpentine, showing much variation—in this case abnormally large.

c. This was followed by the basic—a gabbro, showing in places fluxion banding.

d. The gabbro-pegmatite dykes represent a late stage of the gabbro intrusion.

e. This whole series is cut by numerous dolerite dykes.

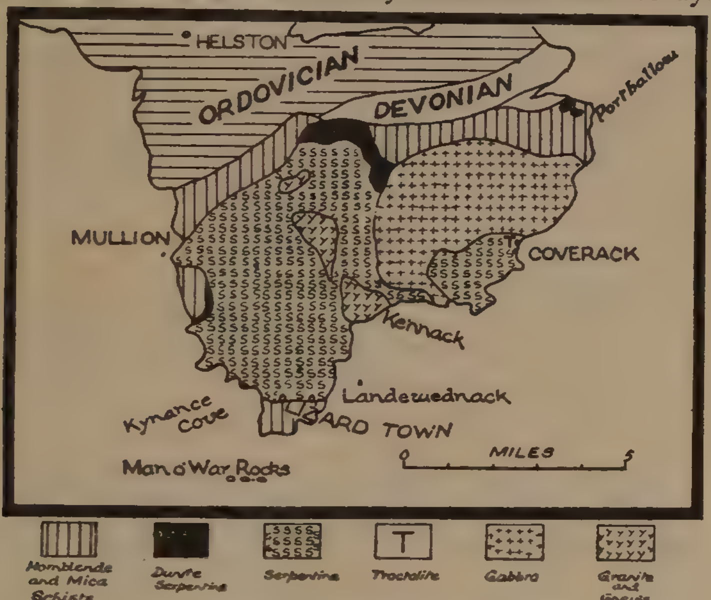

FIG. 9. The Plutonic Complex of the Lizard District. (*S.W.W. and H.C.B.*)

f. The streaky Kennack gneisses follow—they are believed to be an imperfect mixture of the preceding doleritic material with the succeeding granitic.

g. Several small bosses of pale red acid granite.

h. Most of these types of rock show differentiation. For example, there are marginal developments of pure olivine rock (dunite) round the serpentine, and of troctolite round the gabbro. The whole series is magnificently exposed, and can be easily studied.[1]

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[1] A good short account appears in *Proc. Geol. Assoc.*, vol. xxiv. (1913), p. 118. Fuller details may be found in *Mem. Geol. Surv.*, sheet 359, Lizard and Meneage (1912).

START POINT. The highly folded mica- and chlorite-schists are possibly a continuation of the Lizard Series. Eddystone Lighthouse is built on Pre-Cambrian gneisses.

2. South Wales (Pembrokeshire).

A series of sedimentary rocks with abundant interbedded intermediate and acid lavas and tuffs, the whole not less than 5,000 feet in thickness, is found unconformably overlain by Cambrian. They were formerly called "Pebidian," and much resemble the Uriconian of Shropshire. They were intruded by masses of granite, diorite and quartz-porphyry and later by a set of basic dykes. The whole was considerably disturbed and denuded before Cambrian times.

3. North Wales.

NORTHERN CARNARVONSHIRE. A great series of acid volcanic rocks—rhyolites, breccias, tuffs and some grits—stretches from Bangor to Carnarvon, and recurs at Beaumaris in Anglesey. It is penetrated by a mass of aplitic granite at Carnarvon, and the whole is unconformably overlain by the Cambrian Slates of Llanberis. The pre-Cambrian complex reappears at the western end of the Lleyn Peninsula.

ANGLESEY.[1] Two-thirds of this island are occupied by a great complex of crystalline rocks of Pre-Cambrian age—the Mona complex. Out of a complex of some seventy rock types, including representatives of all the commoner types of sediments, spilites and associated jaspers, felsites, tuffs, and plutonic rocks ranging from serpentines to granites, the existence of a number of rock groups has been established by Mr. Greenly. The discovery of pebbles from one group in the conglomerates of another has given definite evidence of the chronological order in which the succession must be read. "Thus we attain the conception of an original bedded succession of six principal subdivisions resting upon an ancient floor of

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[1] See note, p. 102, also "A Short Summary of the Geological History of Anglesey," by E. Greenly (*Thos. Murby & Co.*).

yet older foliated rocks, of which it is conjectured that certain gneisses form the only visible representatives. Into this bedded succession has been intruded a varied suite of plutonic intrusions, and the whole subjected to powerful regional metamorphism." The rocks, as a whole, are highly sodic, the most abundant felspar being albite, and are of a persistently green colour, owing to the presence of chlorite. Annelid pipes and castings seem to indicate the existence of life and the jaspers are suspected to be altered radiolarian cherts. Two or perhaps three great overfolds, with complementary thrusts or slides, are believed to exist, the impulse being from the north-west. If this is correct, extensive folding with a Caledonian trend must have taken place. A great part of the folding is Pre-Cambrian, though later movements followed the same lines. Pebbles from the complex occur in the basal Cambrian conglomerates of Carnarvonshire, and thus the Pre-Cambrian age of the complex is certain.

4. Shropshire.[1]

Most of the types of Pre-Cambrian rocks exist in this county.

a. A small patch of crystalline schists occurs at Rushton (Rushton Schists).

b. A group of Volcanic rocks — the Uriconian—gives rise to a line of hog-backed hills stretching along the line of the great Church Stretton Fault from the Wrekin to near Church Stretton and to the mass near Old Radnor. The principal rock types are rhyolitic and andesitic lavas and tuffs associated with intrusions of aplitic granite. They are also cut by basic sills and dykes of later date. These "Eastern Uriconian" rocks are covered unconformably by Cambrian or later rocks, but their relation with the next group is always obscured by faulting.

c. A group of sedimentary rocks—including conglomerates, sandstones and shales—called Long-

[1] W. F. Whittard, "A Geology of South Shropshire." *Proc. Geol. Assoc.*, vol. lxiii., 1952, pp. 143-197.

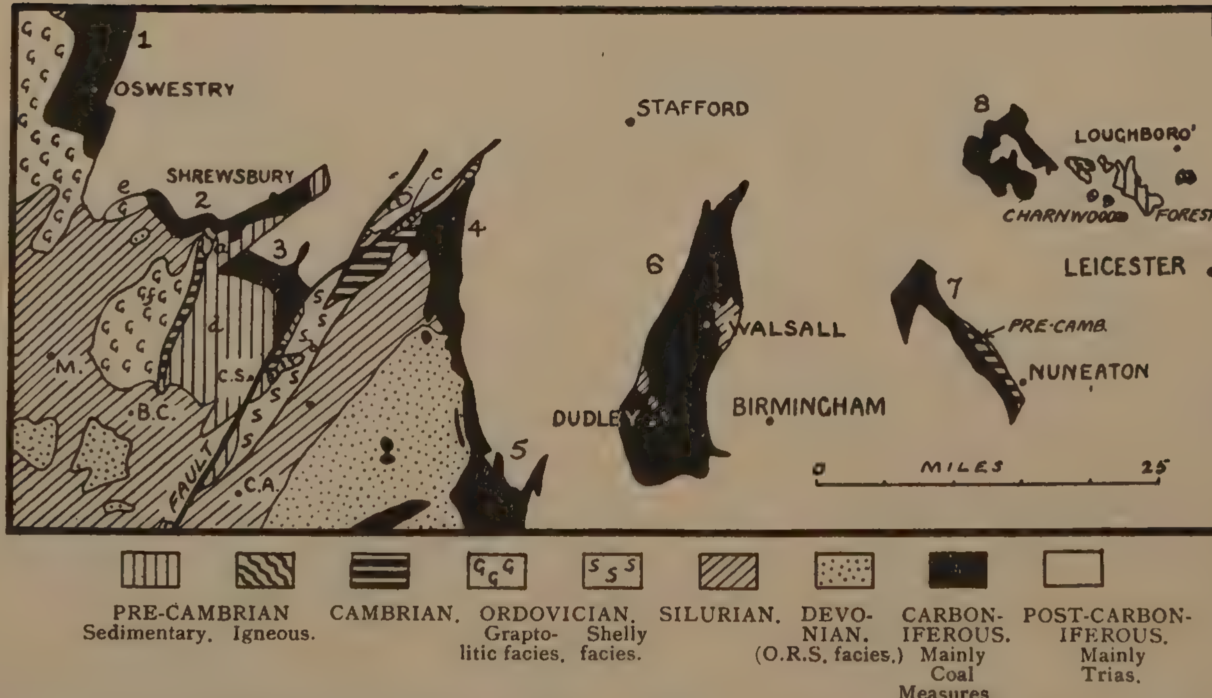

FIG. 10. Geological Sketch Map of the Midlands of England and Shropshire, showing the inliers of Pre-Cambrian, Cambrian, Silurian and Carboniferous Rocks and the location of the two types of Ordovician in Shropshire. Towns: M.=Montgomery; B.C.=Bishop's Castle; C.S.=Church Stretton; C.A.=Craven Arms. Coalfields: 1=part of North Wales Field; 2=Shropshire Coalfield; 3=Leebotwood Coalfield; 4=Coalbrookdale Coalfield; 5=Forest of Wyre Coalfield; 6=South Staffordshire Coalfield; 7=East Warwickshire Coalfield; 8=Leicestershire Coalfield. Some other noteworthy localities: a=Pontesford Hill (Uriconian); b=Caer Caradoc (Uriconian) and Comley (Cambrian); c=The Wrekin (Uriconian); d=The Longmynd e=The Breiddens; f=Shelve District. (*L.D.S.* after *C. Lapworth.*)

myndian forms the wild, moorland tract of the Longmynd, to the west of the great Church Stretton Fault. They are divided into an eastern and a western series. The Western Group agrees very closely with the Torridonian of Scotland, and its conglomerates include numerous pebbles of Uriconian volcanic rocks. Probably both series are newer than the Uriconian, the Western certainly is. An inlier occurs at Old Radnor.

d. On the west the higher beds of the Western Longmyndian seem to pass up into another series of volcanic rocks—forming Pontesford Hill—strikingly similar to the Uriconian. These are generally termed the Pontesfordian or Western Uriconian.

e. The succession in Shropshire therefore seems to be:

5. Western Uriconian.
4. Western Longmyndian.
3. Eastern Longmyndian.
2. Eastern Uriconian.
1. Rushtonian Schists.

5. The Midlands.[1]

MALVERN—the central core of the north and south range known as the Malvern Hills consists of highly crystalline gneissic rocks (" Malvernian "). For the most part these seem to be metamorphosed igneous rocks, but massive diorites and pegmatites also occur There are also volcanic rocks comparable with the Uriconian. Both groups are covered unconformably by Cambrian.

LICKEY HILLS (near Birmingham), and NUNEATON. Volcanic Rocks, probably of the same age as those at Pontesford Hill, are overlain by Cambrian.

CHARNWOOD FOREST: The " Charnian " is a thick series of Pre-Cambrian sedimentary and pyroclastic rocks,

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[1] For details of the several areas see C. Lapworth, " A Sketch of the Geology of the Birmingham District," *Proc. Geol. Assoc.*, vol. xv. (1898), pp. 313-314, a very useful paper. For an interpretation see L. J. Wills' " Palæogeography of the Midlands " (Liverpool, 1948).

disposed in a faulted anticline of Charnian trend, *i.e.*, with axis running from N.W. to S.E. They are to be correlated with the Eastern Longmyndian. " The lower and middle divisions (Blackbrook and Maplewell Series) are pyroclastic rocks of intermediate composition and varying degrees of coarseness, deposited on the flanks of volcanoes, and probably sorted and stratified under water. They pass, however, on the western side of the area, into coarse agglomerates and breccias, probably formed above water, and associated with lavas and massive intrusive rocks." The latter may be described as much sheared rocks allied to dacites. The upper division (Brand Series) is " made up chiefly of terrigenous material transported by water, but deposited while vulcanicity was still in progress in the immediate neighbourhood."

6. Yorkshire.

Near Ingleton a group of sediments, possibly of Pre-Cambrian age, underlies the Ordovician.[1]

C. Ireland.

The Pre-Cambrian areas of Northern and North-Western Ireland are in reality a continuation of the Scottish series. It is doubtful whether Lewisian rocks occur, ancient gneisses do exist, but they seem to have resulted in all cases from an invasion of sedimentary rocks by granite. Practically the whole of the rocks may be called Dalradian, and resemble that group as developed in Scotland. In Donegal and elsewhere there is an interesting " boulder-bed," for which a glacial origin has been claimed.

VULCANICITY IN PRE-CAMBRIAN TIMES.

" It is clear that the Pre-Cambrian history of England and Wales was one of active vulcanicity and the intrusion of igneous rocks, that marine areas were limited in extent and of restricted duration, and that conditions were highly unfavourable for the preservation of fossils." There were at least two volcanic episodes in England and Wales, but volcanic rocks are known in Scotland only as pebbles in the Torridonian. Reference has already been made to the much altered plutonic rocks of Scotland.

[1] One writer believes, however, that these beds are simply the basal members of the Upper Ordovician. See discussion, *Quart. Journ. Geol. Soc.*, vol. lxxxviii. 1932, pp. 100-111.

EARTH-MOVEMENTS IN PRE-CAMBRIAN TIMES.

This subject is too vast to be dealt with here, but we may note in passing—

a. The Charnian folding, so called from Charnwood Forest, is mainly Pre-Cambrian, and is important in the Midlands. The axes of the folds run from N.W. to S.E., and movements along these lines have taken place at intervals from Pre-Cambrian times to the present day—even now many British earthquakes are connected with Charnian lines of movement.

b. Recent work in Anglesey shows that folding with axes S.W.—N.E. (*i.e.*, Caledonian trend) was already important in Pre-Cambrian times.

c. Folding of varying intensity and direction affects the Pre-Torridonian rocks of Scotland. One prominent direction in the North-Western Highlands is approximately east to west.

THE CANADIAN SHIELD.

No account of the Pre-Cambrian would be complete without some reference to one of the world's great areas of these early strata. The succession in the Canadian Shield is as follows:—

Keweenawan.
    Unconformity.
Animikie.
    Great Unconformity: upwelling of later Laurentian granites.
Huronian { Upper. Lower.
    Great Unconformity: upwelling of earlier Laurentian granites.
Keewatin.

The Keewatin is a great series of sedimentary and volcanic rocks. No trace has been found of the early land-surface or sea bottoms on which they were laid down. At the close of the period came a great epoch of mountain building. The upwelling of great bosses of granite caused these sediments to be " pinched in " as irregular synclines between the bosses. After a long period of denudation a glacial age ensued and the lowest **Huronian** deposits are great beds of Boulder Clay. This was followed by a period of marine transgression, with a slight break between the Lower and Upper Huronian. The basal conglomerate of the Upper Huronian is possibly a boulder clay. Then a great mountain-building movement and the uprise of the late " Laurentian " batholiths of granite and gneiss affected the greater part of the Shield, but a broad central band escaped, so that the original relations of the early " Laurentian " granites to the Keewatin is preserved. The **Animikie** rest almost horizontally, on the upturned edges of the earlier rocks. The **Keweenawan** follows with but a slight break, and includes shallow water beds of sandstone and con-

glomerate, accompanied by immense flows of lava. The physiography of the great basins, such as that of Lake Superior, is controlled by the presence of the great lava flows.

From this account it will be seen how far from the truth was the old idea that the Canadian Shield represented part of the original crust of the earth. The same is true of the Scandinavian Finland Mass. We may note in the Canadian succession—

a. Two great periods of earth-movement.
b. Two great periods of igneous intrusion closely connected with the earth-movements.
c. One, possibly two, glacial periods.

ECONOMIC GEOLOGY OF THE PRE-CAMBRIAN.

1. Building Stones. The Pre-Cambrian gneisses and other metamorphic rocks, though much used locally, are usually too fissile to form good building stones. The later intrusive masses which penetrate them are often extremely important — as, for example, the granites of Aberdeen. A few pretty granites of Pre-Cambrian age are quarried (Galway) and other ornamental stones include the Serpentine of the Lizard (Cornwall) and the green marble of Connemara.

2. Road Metal. Much used locally and where transport is easy, sets and curb-stones are shaped from some of the Scottish gneisses. Some of the Pre-Cambrian inliers in the Midlands of England (Malvern, the Wrekin, Nuneaton and Charnwood) are important, as they furnish stone in the midst of a country with few durable rocks (Trias). Road metal from these sources is largely used over the whole of South-Eastern England.

3. Sands. Some of the Scottish Dalradian quartzites are sufficiently pure to furnish a glass sand, but it is doubtful if they would repay the cost of crushing.

4. Felspar. Some Scottish dykes might furnish felspar in marketable quantities, but are little exploited.

5. Metallic Ores. These are not very important in the British Isles, though metalliferous lodes of later date may cut Pre-Cambrian rocks, *e.g.*, the unimportant copper lodes (Carbo-Permian) cutting the Lizard Serpentine.

6. Water Supply. The chief importance of the Pre-Cambrian in this respect is that they give rise to mountain tracts with a high rainfall, and reservoirs can be constructed.

7. Water Power. The water power resources of Britain are limited, but some of the most important developments are in the Highlands of Scotland, notably near Fort William, at Kinlochleven and Pitlochry. Later schemes use water from Glen Affric and Rannoch Moor.

8. Scenery. The Pre-Cambrian rocks are covered by great stretches of barren moorland (Scotland), whose chief use is as game preserves. Forestry is more important than agriculture, but the Scottish Highlands are famous for a hardy race of cattle—the Highland Cattle—and also the Scottish Blackface sheep.

CHAPTER V.

THE CAMBRIAN SYSTEM.

NAME. Cambrian (Sedgwick 1835) from Cambria = Wales. Sedgwick's Cambrian System had no clearly defined upper limit, and for long there was great discussion as to the limit between the Cambrian and Silurian, which was only brought to a close by the recognition of an intermediate system—the Ordovician.

GEOGRAPHY OF THE PERIOD.

As a general rule it may be said the older the system the more difficult is the reconstruction of the geography and conditions of the period. Whilst the maps which illustrate the accounts of the later systems may be looked upon as being very probable or even certain representations of the geography of their respective periods, those which accompany the descriptions of the lower Palæozoic Systems must be regarded more as suggestions. The data available are so slight that it is doubtful whether any but very approximate conceptions of conditions during these early geological times will ever be reached.

1. Most of the Pre-Cambrian sedimentary rocks—especially the Torridonian of Scotland or the Sparagmite of Scandinavia—are coarse torrential deposits which appear to have been laid down in more or less enclosed, mountain-girt basins, perhaps comparable with those of Old Red Sandstone times (see page 114).
2. The history of Cambrian times commenced with the depression of the whole area. Naturally the earlier deposits are coarse arenaceous sediments, the material of which was derived from a variety of sources.
3. This depression seems to have resulted in the formation of a long deep oceanic trough from W.S.W.

to E.N.E. Its northern shore gradually moved northwards, so that in Upper Cambrian times it was well to the north of Scotland. The southern shore was probably fringed by numerous large islands—hence shallow water conditions prevailed over considerable areas—but gradually these were submerged, and but mere remnants remained at the end of the period. The main shore was probably situated to the south of Devon and Cornwall.

4. Certain remarkable characters are exhibited by Cambrian faunas—especially Upper Cambrian faunas.[1] There is a great resemblance between the faunas of the Scottish Cambrian and that of the "Western Province" of North America. Yet the Scottish fauna is extraordinarily different from that of Wales, but the latter shows some affinities with that of the "Eastern Province" of North America (*i.e.*, east of the Alleghanies). It is mainly on this evidence that it has been supposed that the main sea or trough extended right across the Atlantic Ocean, the Archean masses of the Canadian Shield, Shetland Isles and Scandinavia being remnants of the mountains which formed its northern shore. The southern shore would have run from the old land of "Appalachia" across the Atlantic to embrace Brittany, and on into Central Europe, possibly running as far south as the Central Massif of France. The Cambrian faunas migrated along the shores of this ocean, but, like shallow-water faunas of the present day, were unable to cross the deep trough from side to side. Some further details have been incorporated in the sketch map (*Fig.* 11). The difference between the Cambrian faunas of the Baltic provinces and Bohemia suggests a barrier between the two.

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[1] B. N. Peach, Pres. Add. Section C, *Rep. Brit. Assoc.* (Dundee), 1912.

FIG. 11. Map showing the distribution of the Cambrian Life Provinces of Europe and North America and the probable Palæogeography of Lower Cambrian times. Closely-spaced vertical lines indicate the principal existing areas of Pre-Cambrian strata. Broadly-spaced vertical lines indicate the land of the period. It should be noticed that the Pre-Cambrian massifs are grouped on either side of the long, narrow, but deep, oceanic trough. Map on Gall's Projection. (*L.D.S.*)

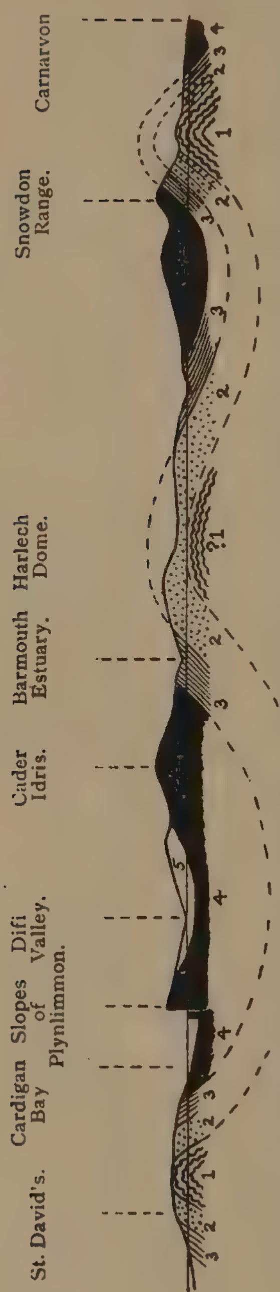

FIG. 12. Diagrammatic Section across Wales from South to North, showing the Anticlinal Areas of Cambrian Rocks. 1, Pre-Cambrian; 2, Lower and Middle Cambrian; 3, Upper Cambrian; 4, Ordovician; 5, Silurian. Horizontal Scale about 10 miles to one inch. (*L.D.S.*)

THE CAMBRIAN IN GREAT BRITAIN.

From what has been said above it follows that the Cambrian of Great Britain falls into two provinces :—

1. England and Wales (Welsh Province), including—

a. Wales (Welsh or Merioneth Facies).

b. Midlands of England (Shropshire Facies).

c. Lake District and Isle of Man.

2. Scotland (Scottish Province, with Highland Facies).

1. England and Wales (Welsh Province).

a. Wales.

In a consideration of the Cambrian these two important factors should be borne in mind :—

(i) Gradual sinking during the period.

(ii) Presence of local land masses.

The Cambrian rocks occur in three principal areas :—

(i) Pembrokeshire,
(ii) The Harlech Dome,
(iii) Carnarvonshire,

where they emerge as anticlinal areas from beneath Ordovician rocks as shown in the diagrammatic section (*Fig.* 12).

The general classification adopted for the Cambrian is—

Upper Cambrian	Transition Series	=	Tremadoc Slates.
	Olenus Series	=	Lingula Flags.
Middle Cambrian	*Paradoxides* Series	=	Menevian Slates. Upper Harlech Beds of North Wales, Solva Series of South Wales
Lower Cambrian	*Olenellus* Series	=	Lower Harlech Beds of N. Wales, Caerfai Series of S. Wales.

NOTE.—The Tremadoc Slates are now very frequently regarded as Ordovician.

(i) PEMBROKESHIRE (St. David's area, towards the north coast, etc.).

The *Olenellus* or Caerfai Series consists of conglomerates, red and purple sandstones and flags with very few fossils. The *Paradoxides* Series includes the Solva Beds of grey, purple or red sandstones, flags and some slates, and the Menevian Beds of dark flags and black slates, with several species of *Paradoxides*. The gradual change to sediments of a deeper water type should be noted. The *Olenus* Series (Lingula Flags) are of shallower water type. *Lingulella davisi* is the characteristic fossil. The Tremadoc Series is not definitely known to occur, and there is a break between the basal Ordovician and the Cambrian.

(ii) THE HARLECH DOME.

In this stretch of barren, desolate moorland is exposed the grandest succession of Lower Cambrian strata in the country, and round the dome the Middle and Upper Cambrian crop out in successive rings, somewhat interrupted by faulting and minor folding.

The *Harlech Series* consists of varied sediments—up to 6,000 feet in thickness — but has two important horizons of massive sandstones, the Rhinog Grits 2,500 feet in thickness below, and nearer the top of the series the Barmouth Grits 600 feet thick. Between the two is a band with a considerable content of manganese ore, and formerly worked for its extraction. The series is practically unfossiliferous except for the occurrence of worm-tracks. The base is not seen.

The *Menevian Series* follows conformably, and comprises sediments of deeper water type, including black slates with numerous fossils, such as *Paradoxides davidis*, *Agnostus fissus* and *Microdiscus punctatus*. The *Lingula Flags*, characterized by *Lingulella davisi*, as well as by *Olenus* (*O. spinulosus*) and other trilobites (*Agnostus trisectus* and *A. princeps*), comprise shallow-water sediments in the lower part passing upwards into deeper water beds (intensely black shales). Three stages are distinguished—

3. Dolgelley Stage.
2. Ffestiniog Stage.
1. Maentwrog Stage.

There is a well-marked fossiliferous band at the top of the Ffestiniog Stage (*Lingulella davisi*). The Dolgelley Stage, though thinner than the two lower, probably represents a longer period of time, and has been divided into four zones.

The *Tremadoc Slates* (see note above on the Ordovician age of these beds) are characterized by the trilobites *Niobe homfrayi* (lowest beds), *Asaphellus homfrayi* (higher beds) and *Angelina sedgwicki* (highest part), and by the dendroid graptolites *Dictyograptus* [*Dictyonema*] *socialis* and *Bryograptus callavei*. One band very rich in *Dictyonema* (the Lower *Dictyonema* Band) occurs with some unfossiliferous slates between the *Niobe* and *Asaphellus* Beds; another (the Upper *Dictyonema* Band) has recently been recorded in the Dolgelley District from the top of the *Asaphellus* Beds. Succeeding the latter are mudstones with *Shumardia* and numerous trilobites. The highest beds are the *Angelina* Beds.

The sequence of volcanic activity in late Cambrian or early Ordovician times has been fully worked out in the Rhobell Fawr mass by Dr. A. K. Wells (see *Quart. Jour. Geol. Soc.*, lxxxi., 1925).

(iii) CARNARVONSHIRE.

When the Cambrian reappears from beneath the Snowdon Syncline (see *Fig.* 12) the sediments are much finer in character, and constitute the Llanberis Slates. There are a few grit bands in the lower part. The beds are perfectly cleaved, and have been much quarried and mined for roofing slates.

The Tremadoc Series is absent from the Llanberis district, and in Anglesey the whole of the Cambrian appears to have been overlapped, and is nowhere exposed.

FIG. 13. Map of the British Isles, showing the Outcrops of Cambrian Strata. I—I, I—I, Line of Section (Fig. 12).

b. The Midlands of England.[1]

The Cambrian of the Midlands appears in a number of small isolated areas: Malvern, Pedwardine (in the north-

[1] See "Geology in the Field," also C. Lapworth and W. W. Watts, *Proc. Geol. Assoc.*, vol. xv. (1898), pp. 313-416.

eastern corner of Herefordshire), Shropshire, the Lickey Hills and Nuneaton. Although the succession is not usually complete in any one district, in nearly all of them the lower beds (Lower Cambrian) are sandstones and quartzites, and the higher beds (Middle and Upper Cambrian) are deep-water shales. Between these two lithological types there is sometimes a development of limestone or calcareous sandstone. Naturally it is difficult to correlate the beds in such small and widely separated localities, and so local names are much in use, as shown in the following table :—

	Full succession.	Shropshire.	Nuneaton.	Malvern Hills.
U.C.	*Shumardia* Beds. *Dictyonema* Beds. *Olenus* Shales.	Shineton Shales.	Stockingford Shales	Bronsil Shales. White-leaved Oak Shales.
M.C.	Menevian Shales. *Paradoxides* Limestone	*Paradoxides* Grits and Shales.		Hollybush Sandstone.
L.C.	*Olenellus* Sandstone. Quartzite.	Comley Sandstone with Limestones. Wrekin Quartzite.	Quartzite	Malvern Quartzite.

The SHROPSHIRE Succession has been studied in great detail by Mr. E. S. Cobbold, especially at Comley, near Church Stretton. The Wrekin Quartzite is conglomeratic at the base, and rests unconformably on the Pre-Cambrian volcanic rocks. The Comley Sandstone has *Callavia* [*Olenellus*] *callavei* in the lower part, and includes bands of limestone in the higher parts. The overlying grits have *Paradoxides groomi*. The Shineton Shales are better seen south of the Wrekin than at Comley. The faunas have been studied in detail by Dr. C. J. Stubblefield and Dr. O. M. B. Bulman,[1] who distinguish six beds. From the bottom upwards these are (1) Zone of *Dictyonema flabelliforme*, (2) Transition Beds, (3) Zone of *Clonograptus tenellus*, (4) Brachiopod Beds, (5) Zone of *Shumardia pusilla* (closely comparable with the *Shumardia* Beds of North Wales) and (6) Arenaceous Beds.

At PEDWARDINE the *Dictyonema* Beds are known.

In the LICKEY HILLS (near Birmingham) an unfossiliferous quartzite with a basal conglomerate—consisting largely of pebbles of Pre-Cambrian rocks—and overlain

[1] *Quart. Jour. Geol. Soc.*, vol. lxxxiii. (1927), pp. 96-121.

unconformably by Valentian occurs. It resembles the Wrekin and Nuneaton Quartzites, and hence a Lower Cambrian age is assumed.

North and North-West of NUNEATON resting unconformably on Pre-Cambrian volcanic rocks are grits and conglomerates, yielding an *Olenellus* fauna in the upper part. The overlying Stockingford Shales have been divided into :—

3. Grey or Merevale Shales	*Dictyonema* fauna.
2. Black or Oldbury Shales	*Lingula* Flags fauna. *Paradoxides* fauna.
1. Purple or Purley Shales	*Olenellus* fauna.

Borings at LEICESTER and at CALVERT in Buckinghamshire have struck Upper Cambrian Shales.

In the MALVERN HILLS fragments of Pre-Cambrian rocks are found in the Malvern Quartzite. The succeeding Hollybush Sandstone has *Hyolithes,* the White-Leaved Oak Shales have yielded a *Lingula* Flags fauna, but probably represent much lower beds also, whilst the Bronsil Shales have *Dictyonema* at the base, as well as *Dictyonema* and *Niobe* in the upper part.

c. Lake District and the Isle of Man.

In the LAKE DISTRICT the highest part of the Skiddaw Slates are of Arenig age, but it is highly probable that the bulk of them are Cambrian. The Skiddaw Slates are much cleaved and metamorphosed by pressure and by the intrusion of igneous masses, and they cover a large area in the core of the Lake District. Apart from the beds with an Arenig fauna, they have yielded the dendroid graptolite *Bryograptus.* In the ISLE OF MAN a large area is also occupied by very similar slates (the Manx Slates and Lonan Flags). It may be that these slates of the Lake District and the Isle of Man are the deposits of the deeper parts of the great oceanic trough, whilst the Welsh beds were laid down in the more littoral parts.

In IRELAND a series of crushed and folded slates and quartzites occurs in the east of Leinster. They have fan-shaped markings which have been called " *Oldhamia radiata* " and " *O. antiqua.*" They seem linked to the Manx Slates in general characters.

Linked with the English Cambrian by their faunas rather than with the Scottish (Highland) type are the presumably Cambrian rocks of KINCARDINESHIRE and other points along the southern border of the Scottish Highlands. They yield various hingeless brachiopods.

2. Scotland (Scottish Province).

Occupying a narrow belt between the Torridonian Sandstone on the west and the great mass of the "Eastern Schists" on the east, there are about 2,000 feet of strata in the North-West Highlands assigned to the Cambrian. The succession is as follows:—

3. Durness Limestone with fossiliferous bands.
2. *Olenellus* Beds ("Serpulite Grit" and "Fucoid Beds").
1. Basal Quartzites and Grits.

At the base is a thin conglomerate, succeeded by false-bedded flaggy grits and quartzites. The upper beds are fine-grained quartzites perforated by vertical worm casts (hence the name "Pipe Rock"). Curiously enough the size and form of the "pipes" vary from bed to bed.

Both the Fucoid Bed (so called from the flattened worm casts resembling algæ or "fucoids") and the Serpulite Grit (from the presence of *Salterella*, formerly called a "worm" *Serpulites*) are fossiliferous and the fauna shows strong American affinities (*Kutorgina labradorica, Olenellus lapworthi, O. gigas*, etc.). The Durness Limestones consist chiefly of grey dolomites, with bands of true limestone and chert nodules. Seven stages have been distinguished; in all of them trilobites are very scarce, and as the other fossils have an American facies, it is impossible to correlate the succession with that of Wales. It should be noted that some geologists consider the higher beds are of Ordovician age.

ECONOMIC GEOLOGY OF THE CAMBRIAN.

1. Building Stones. None of importance.

2. Road Metal. The Cambrian Quartzites of the Midlands are, like the Pre-Cambrian rocks there, of importance from their occurrence as inliers in the midst of plains of soft Trias. The intrusive rocks—of doubtful age—are often more important than the sedimentary, as at Nuneaton.

3. Roofing Slates. The Cambrian Beds of North Wales furnish the famous Llanberis Slates—probably the finest roofing slates

in the world. The hills at the back of Carnarvon—the foothills of the Snowdon Range—are simply riddled with slate-quarries, and the best "veins" may be followed far underground in mines. Great rectangular blocks are cut out by wire saws, and the natural action of rain and frost is often utilized in splitting these up into the actual roofing slates. The value of the slates depends on their colour and the magnificently developed slaty cleavage. From a commercial point of view the Cambrian Slates elsewhere (Dolgelley, Lake District, etc.) are of minor importance.

4. Ores. Gold occurs in quartz veins (of doubtful age) in the Cambrian of the Harlech Dome. The veins of Lead and Zinc in the Skiddaw Slates of the Lake District are more definitely associated with later igneous intrusions. Manganese, occurring in a bed of the Harlech Series, was formerly mined in North Wales.

5. Scenery. The sandy beds give rise to stretches of desolate, almost uninhabited moorland (Harlech Dome); the slates are more fertile and often wooded, but the scenery tends to be controlled by intrusive masses of a later date.

LIFE OF THE PERIOD.

By far the most important members of the Cambrian fauna are Trilobites and horny inarticulate (hingeless) Brachiopods. The articulate Brachiopod *Orthis* becomes important from the Middle Cambrian upwards and Dendroid Graptolites in the Tremadocian, true Graptolites being absent. Representatives of most of the invertebrate groups occur, but many of them show primitive characters; or one group may combine two sets of characters, each of which afterwards becomes limited to a single group.

a. Arthropoda. Trilobites have furnished the most useful zonal fossils. They consist of three parts, a cephalon or head shield of five fused segments, a thorax of a variable number of segments and a pygidium or tail, and they exhibit certain definite evolutionary tendencies. The Lower Cambrian Trilobites have a large head-shield, a very large number of spinous thoracic segments and a minute pygidium (*Olenellus, Callavia*). In the Middle Cambrian the allied *Paradoxides* often reaches very large dimensions, whilst in the Upper Cambrian the more advanced *Olenus, Niobe, Angelina* and *Asaphus* have smaller head-shields, fewer thoracic segments, a larger and more differentiated pygidium. The curious little *Agnostus*, with rounded head-shield and pygidium very much alike, and separated by two thoracic segments, becomes important in Middle and Upper Cambrian. Other arthropods, such as the Ostracods (*Leperditia*) are said to occur even in Lower Cambrian. *Hymenocaris* may be mentioned as a Cambrian arthropod.

b. Mollusca. Gastropods alone are certainly known to occur in the Cambrian, and are mostly simple, uncoiled forms (*Hyolithes, Salterella* and *Conularia*), coiled forms (*Bellerophon*) occur in Upper Cambrian.

c. Brachiopoda. Of the horny Inarticulata *Lingulella, Kutorgina, Obolella,* etc., all range from the Lower Cambrian. The articulate *Orthis* (*O. lenticularis,* etc.) becomes important in Middle and Upper Cambrian.

d. Echinodermata. The primitive Cystids (*Eocystis*) range from Lower Cambrian, and Crinoids also appear.

e. Cœlenterata. The bush-like colonies of the Dendroid Graptolites (*Dictyonema*) are characteristic of the Tremadocian. The problematical group of the Archæocyathineæ attained world-wide distribution in the later part of the Middle Cambrian (especially in limestones, as in Scotland). The group has many characters intermediate between the corals and sponges.

f. Protozoa. Radiolaria are recorded. Various "worms" and doubtful organisms include "*Serpulites*," "*Oldhamia*" (Cambrian of Ireland), etc.

CHAPTER VI.

THE ORDOVICIAN SYSTEM.

NAME. Ordovician (Lapworth 1879) from the Ordovices, an ancient British tribe formerly inhabiting that part of Wales in which the system is well developed.

It is necessary to state at the outset that although the Ordovician rocks have been studied in great detail in many parts of the British Isles, and are now divided into a number of fairly well defined zones, there is at the present time great difference of opinion as to the number, definition and nomenclature of the larger divisions. For that reason it has been considered advisable to commence this account, contrary to the method adopted in the description of other systems, by a tabular classification, so that the reader will be able to compare this account with details given in other works.

<table>
<tr><th colspan="2">Grouping adopted here.</th><th>Graptolite Zones.</th><th>Alternative Grouping.</th></tr>
<tr><td rowspan="6">BALA</td><td rowspan="3">Ashgillian</td><td>Small Climacograptids</td><td rowspan="6">Bala (Wales) or Caradoc (Shropshire)[1] or Hartfell (Scotland)</td></tr>
<tr><td>Dicellograptus anceps</td></tr>
<tr><td>Dicellograptus complanatus</td></tr>
<tr><td rowspan="3">Caradocian</td><td>Pleurograptus linearis</td></tr>
<tr><td>Dicranograptus clingani</td></tr>
<tr><td>Climacograptus wilsoni</td></tr>
<tr><td colspan="2" rowspan="3">LLANDEILIAN</td><td>Climacograptus peltifer</td><td rowspan="4">Llandeilo (Wales) or Glenkiln (Scotland)</td></tr>
<tr><td>Nemagraptus gracilis</td></tr>
<tr><td>[Ogygia buchi] [2]</td></tr>
<tr><td colspan="2" rowspan="2">LLANVIRNIAN</td><td>Didymograptus murchisoni</td></tr>
<tr><td>Didymograptus bifidus</td><td rowspan="3">Skiddavian or Arenig</td></tr>
<tr><td colspan="2" rowspan="2">ARENIGIAN</td><td>Didymograptus hirundo</td></tr>
<tr><td>Didymograptus extensus</td></tr>
</table>

[1] The Caradoc of Shropshire only includes the lower part of the Bala.

[2] The difficulty expressed here and in the following paragraph has recently been surmounted by the recognition of a graptolite zone (*Glyptograptus teretiusculus*) in this position.

Reference has already been made to the growing tendency to regard the Tremadoc Slates as the base of the Ordovician. In addition, there is great diversity of opinion as to the division line between the Llandeilian and Bala Series. In South Wales, overlying the Llanvirnian, come the Llandeilo Limestones and Calcareous Shales, characterized by the *Ogygia buchi* trilobite fauna. Although it occurs to some extent associated with this *Ogygia* fauna, the *Nemagraptus* graptolite fauna characterizes especially the overlying shales, which are, perhaps rightly, *made the base of the Bala* by some. This is very important in determining the age of the volcanic rocks of North Wales since the *Nemagraptus* fauna occurs in the midst of the volcanic rocks at Llanwrtyd and in the shales or limestone *which immediately overlie them* at Llanwrtyd, Cader Idris, Bala and Arenig (reference being to the highest volcanic series in each case).

GEOGRAPHY OF THE PERIOD.

It has already been noted that in Cambrian times there was a great oceanic trough or geosyncline stretching from Western Europe across to America. Repeated examples show that such a condition is one of instability —at the present day the frequency of earthquakes in Japan illustrates the instability of a region of the Earth's crust where high mountains and a deep ocean trough are in juxtaposition. After some time the deep trough tends to crumple or buckle, and the change is accompanied by a manifestation of volcanic or seismic phenomena. The history of the Ordovician period, as well as that of the succeeding Silurian, is very largely the story of the buckling of the Cambrian trough. The general sequence of events seems to have been:—

1. Towards the close of Cambrian times there were already signs of change. In the *Lingula* Flags of North Wales shallower water conditions temporarily interrupted the general tendency to a deepening of the sea seen elsewhere. Probably also slight volcanic activity was manifest at the end of the period.[1]

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[1] See note on page 70 regarding the Rhobell Fawr volcano.

2. In late Cambrian or earliest Ordovician times extensive folding took place so that in most localities the basal Arenig rock is a conglomerate resting unconformably on underlying rocks. Whilst the limits of systems should be defined on a palæontological basis — *i.e.*, by means of fossils—as affording the only reliable means of international correlation, it is a great advantage to have also a stratigraphical break, such as an unconformity, at the base of a system.[1] Moreover, the change of conditions indicated by such breaks is often to be traced over enormous tracts of country. Thus a classification which duly recognizes their importance is as natural a classification as it is possible to have of what is really a record of continuous time—the Geological Record. This is one argument for placing the base of the Ordovician System at the base of the Arenig Grit. On the other hand, palæontological evidence seems to favour placing the base of the system at the base of the Tremadoc Slates.

3. The direction of the axes of the folds was parallel to the long axis of the trough, roughly N.E. to S.W. This is the same direction as that followed by the later Caledonian earth-movements at the end of the Silurian. The Ordovician folds are gentler than those produced by the later movements, and the two sets may sometimes be distinguished in the same district. There may also be a difference of 15° or 20° in the directions of the two sets.[2]

4. One result of this early folding is that Ordovician rocks present two distinct facies :—

a. A deep-water facies represented by shales and mudstones, in which the principal fossils are graptolites.[3]

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[1] Compare Fig. 3. It is obviously better to use the plane of unconformity as the base of the upper series rather than a base defined on purely palæontological grounds where the deposition has been continuous in the centre of the basin.

[2] J. F. N. Green, "The Geological Structure of the Lake District," *Proc. Geol. Assoc.*, vol. xxxi. (1920), pp. 109-126.

[3] Recent work makes it increasingly doubtful whether graptolitic shales are *necessarily* deep water, though they must have been deposited in comparatively tranquil conditions. See discussion on Prof. W. J. Pugh's and Prof. W. B. R. King's papers, *Quart. Jour. Geol. Soc.*, vol. lxxix., 1923, pp. 541-545.

b. A shallow-water facies represented by sandstones with occasional limestones and shales, in which the important fossils are brachiopods and trilobites (shelly facies).

The latter facies can be considered as belonging to the deposits of shallow continental shelves or the shallow-water regions round a number of tectonic and volcanic islands, whilst but a short distance away the graptolitic mudstones were being laid down in steep-sided comparatively deep troughs. The changes from one type of sediment to the other are often remarkably sudden. The graptolitic shales are usually much thinner than the more rapidly formed coarser deposits.

5. Early in the period volcanic activity broke out—as, for example, in South-Eastern Carmarthenshire—but the first great outburst took place in Llanvirnian times, and reached its maximum in the time of the zone of *Didymograptus murchisoni*. It should be noted that on the whole the earlier outburst is most fully developed towards the south, that is, towards the southern shoreline of the old geosyncline; and also near the Highland border in Scotland, that is, towards the northern shoreline.[1] The Ordovician sea became studded with submerged or partly submerged volcanoes, which at times burst forth with great explosive action, and gave rise to great beds of breccia and ashes, at other times poured forth masses of lava. The majority of the volcanic rocks belong to the suite, very rich in soda, which has come to be regarded as characteristic of submarine volcanic action, or of volcanic action accompanying slow submergence. The submergence is indicated by the presence of the deep-water graptolitic rocks. This suite is the Spilitic Suite, its most characteristic lavas are the basic Spilites or Pillow-lavas, and the more acid keratophyres and quartz kera-

[1] An important exception to this, fully studied by Dr. A. K. Wells, is the Rhobell Fawr volcano, east of the Harlech Dome. Here, after the deposition of the Tremadoc Beds, volcanic activity burst out and the lavas are covered by what are in neighbouring areas the basal beds of the Arenig. That the volcano was sub-aerial, shows that the Tremadoc beds must first have been uplifted. See *Quart. Jour. Geol. Soc.*, vol. lxxxi., 1925, pp. 531-533.

tophyres or "soda rhyolites." The older writers referred to the basic and acid rocks as "greenstone" and "felsite" respectively. The acid types can often only be distinguished from more normal acid lavas (rhyolites, etc.) by chemical analysis.

6. The first great volcanic outburst had scarcely died down and its lavas covered by sediments when a second outburst, almost as extensive as the first, broke out. The crustal movements associated with the first outburst had been mainly of the nature of slow subsidence. Now an element of lateral thrust is apparent, and amongst the new volcanic rocks the andesitic series (Pacific Suite) becomes conspicuous, though the spilitic series is still very important. Though formerly referred to as the "Bala Volcanic Series," this second outburst reached its height towards the close of the Llandeilo period (as defined above[1]), and died down almost everywhere in the Caradocian. It should be noted that the main region of activity had moved more towards the centre of the old geosyncline, *i.e.*, North Wales. Vulcanicity was prolonged into the Caradocian, in the Berwyns,[2] and in Shropshire, and even into the Ashgillian in the Lake District. With the exception of small occurrences in the Silurian (S. Wales—Mendips area), there was no more volcanic activity until the Devonian period, and that was of a very different character.

7. A considerable thickness of sediment was then laid down, and the Ordovician sea wore away and encroached on some of the islands. Thus the earliest Ordovician rocks on the eastern side of the Longmynd in Shropshire are Caradocian in age.

8. The Ordovician period was brought to a close by far-reaching though not very intense earth-movements giving rise to extensive land areas. The Cambrian geosyncline was largely filled in, and the folding and thrust-

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[1] See note at foot of table. The volcanic rocks of this episode are usually immediately overlain by deposits with the fauna of the Zone of *Nemagraptus gracilis*.

[2] For a summary of the sequence of events in this area see W. B. R. King, *Quart. Jour. Geol. Soc.*, vol. lxxix, 1923, pp. 502-503.

ing movements, which were to culminate in the Caledonian system of folding at the end of the Silurian, had commenced. Many of the small intrusive rocks of Wales are closely associated with the Ordovician volcanic rocks, others are probably of Silurian age.

9. The evidence afforded by the various Ordovician faunas is of particular interest in the history of the period.

a. The graptolitic faunas, being of deep-water type, or at least characteristic of tranquil conditions, are of wide distribution. Not only can the same zones be traced in all the Ordovician areas of this country, but the succession still holds in most parts of Europe and to a considerable extent in America.

b. There are *two* principal types of shelly fauna. In early Ordovician times, exactly as in Cambrian, one fauna (the trilobites are *Cheirurus*, *Lichas* and *Encrinurus*) characterizes the Scottish beds; another (trilobites are *Asaphus*, *Calymene* and *Trinucleus*) is essentially English. Later in the period the Scottish fauna spread and by Ashgillian times dominated the whole of the British region. Doubtless the buckling of the old trough allowed a shallow-water fauna to cross the area—a migration impossible in Cambrian times. The invading or Scottish fauna has "exotic" characters—viz., American affinities: it would seem then that the ocean was still open from America to Europe in Ordovician times.

10. It is difficult to construct a map of the actual geography of the period. Amongst the islands already mentioned as fringing the southern shore may be noted:—

a. Part of Anglesey and an area to the west.[1]

b. The Longmynd of Shropshire and a large area to the east The region immediately to the east of the Longmynd was covered by the sea in Caradocian times. Ordovician rocks have not been found in England to the east of the longitude of Shropshire, either at the surface or in deep borings, and it is possible that the whole of this region was land.

THE ORDOVICIAN IN ENGLAND AND WALES.

Until recently on most geological maps a huge tract covering much of Central and Northern Wales is coloured

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[1] It is often difficult to define former shorelines by existing landmarks. A great thrust plane has brought close together the Ordovician deposits of North and South Anglesey. Whilst the former were laid down near a shoreline, the latter are typical deep-sea deposits.

as Ordovician. Whilst recent study has shown that a great part of this area is occupied by Silurian rocks, the region occupied by Ordovician sediments is still very extensive (see map, page 108). The rocks have been affected not only by the buckling of the old trough in Ordovician and Silurian times, but also by the great earth-movements of Siluro-Devonian age, and again by the later Carbo-Permian folding. All these movements produced folds running approximately from south-west to north-east (" Caledonian " trend), and at the same time the rocks were minutely plicated, cleaved and faulted. For these reasons it is difficult to give a general account of the Ordovician of Wales, although certain areas have been studied in great detail.

1. South Wales (Pembrokeshire, Carmarthenshire, etc.).[1]

The relation between the lowest Ordovician and the Cambrian is often difficult to determine. Briefly the history of the period is :—

a. Shallow water conditions obtained in lower Arenigian times, and are marked by conglomerates, sandstones, etc. An outburst of volcanic activity ensued near the edge of the old trough (subaerial lava flows), giving 2,900 feet of igneous rocks in Skomer Island. There are many curious types of rock present, which were extruded in the order acid to basic and then back to acid, and are accompanied by a few intrusive rocks. The lavas are mostly types rich in soda (soda-rhyolites, soda-trachytes and skomerites, etc.), but were not formed under exactly the same conditions as the true spilitic rocks which characterize the later Ordovician. Other igneous rocks occurring at Llangynog may be of the same age.

b. Gradual subsidence followed in later Arenig and Llanvirn times, giving a great thickness of black grapto-

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[1] A. H. Cox, *Quart. Jour. Geol. Soc.*, vol. lxxi. (1915), pp 273-342; *Mem. Geol. Surv.*, especially Sheets 228, 229 and 230.

litic shales. The subsidence was accompanied by volcanic outbursts — especially marked in the zone of *Didymograptus murchisoni.* The base of this zone is often formed by an ash and considerable thicknesses of soda-rhyolites and rocks of the spilitic suite occur in Pembrokeshire.

c. Then followed a shallower water period, during which the Llandeilo Limestones and Flagstones were deposited. Characteristic fossils are the trilobites *Ogygia buchi, Asaphus tyrannus* and *Calymene cambrensis.* Volcanic rocks are usually absent.

d. A period of subsidence again followed, during which the *Dicranograptus* shales were deposited. It is difficult to draw a line between the Llandeilian and Bala in the midst of this series of shales, but about the centre is a calcareous band (Mydrim Limestone) which has *Nemagraptus gracilis.* The upper part of the shales yields *Climacograptus wilsoni.*

e. The higher Ordovician beds (Caradocian and Ashgillian) are again shallow-water rocks — sandstones and limestones with numerous trilobites (*Encrinurus, Cheirurus, Illænus, Trinucleus concentricus,* etc.). Notice the arrival of the Scottish-American forms referred to above.

2. Central Wales.

Passing northwards or north-eastwards along the Towy anticline (see page 10) there is an increase in thickness of beds on the horizon of the Mydrim Limestone (zone of *Nemagraptus*), and a typical series of spilitic volcanic rocks is found on this horizon near Llanwrtyd. This area forms a connecting link with North Wales, and the succession at Llanwrtyd is closely comparable, though reduced, with that at Cader Idris.[1] At Builth there is an extensive development of igneous rocks, probably on two different horizons, viz., Llanvirn and Llandeilo-Bala.

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[1] L. D. Stamp and S. W. Wooldridge, *Quart. Jour. Geol. Soc.*, vol. lxxix, (1923), pp. 16-46

3. North Wales.[1]

Ordovician times in North Wales were remarkable for the great outbursts of volcanic activity at two main periods, (a) Llanvirn, (b) Llandeilo-Bala. The sequence in the Cader Idris district may be taken as typical.

Great series of mudstones and slates	Bala.
Acid lavas and ashes	Llandeilo-Bala.
Mudstones Spilitic lavas Mudstones and ashes Mudstones	Llandeilian.
Spilitic lavas and ashes Slates with *Didymograptus bifidus*	Llanvirnian.
Acid lavas and ashes Basement sandstones	Arenigian.

There is a small unconformity at the base. The great masses of volcanic rock—the numerous lava flows are nearly all of the spilitic suite—which are found in many parts of North Wales may be correlated with the two main horizons :—

(1) Llanvirnian mainly but commencing in Arenigian, and prolonged into Llandeilian times—including the lower series of Cader Idris and Arenig Mountain.

(2) Llandeilian-Bala. Upper series of Cader Idris, Arenig and main lavas of Snowdon range[2] and Bala District. Overlain immediately by shales or the Derfel Limestone, with *Nemagraptus*-fauna, *Dicranograptus*, etc.

On the whole, the sediments associated with the lavas are of deep water, graptolitic type. The higher Ordovician beds are represented by shallower water limestones

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[1] British Regional Geology: North Wales, 2nd Ed., 1948.

A. H. Cox and A. K. Wells, *Quart. Jour. Geol. Soc.*, vol lxxvi. (1920), especially pp. 257-280 and 318-320; A. H. Cox, *Ibid.*, vol. lxxxi. (1925), pp. 587-589 (Cader Idris); A. Howel Williams, *Ibid.*, vol. lxxxiii (1927), pp. 424-426 (Snowdon); G. L. Elles, *Ibid.*, vol. lxxviii (1922), p. 132-144.

[2] On the sequence in the Snowdon range see the paper by Howel Williams quoted above.

and sandstones, with numerous trilobites. Several distinct trilobite faunas can be distinguished, including the exotic (Scottish-American) one. In the Bala District the volcanic rocks are overlain,[1] as already mentioned, by the Derfel Limestone and *Dicranograptus* Shales (probably representing the higher part of the *Nemagraptus* Zone and the *Climacograptus peltifer* Zone). The overlying beds—undoubted Caradocian — comprise a great thickness of sandstones with limestone-nodules, followed by a series of mudstones. The sandstones and mudstones are separated by an ash-band, and there is another above the latter. The highest Caradocian Beds are Calcareous Ashes, with lenticles of limestone, including what has been called the "Bala Limestone." The Ashgillian is represented by mudstones and sandstones, with the Rhiwlas Limestone near the base.

In Anglesey the Ordovician is complete, and "save for the basal conglomerates and grits is graptolitic throughout, there being a complete passage from an Arenig and Llanvirn of typical Welsh character into a Glenkiln and Hartfell of striking similarity to the Scottish succession." On the northern coast an entirely different facies is developed, and the Arenigian is absent. The two types have been brought into juxtaposition by a great thrust fault.

4. Cornwall.

In the south of Devon and Cornwall (Lizard and Start Point areas) certain of the "killas" and contorted sediments are of Ordovician age. They are associated with spilites and radiolarian cherts, well seen in the Lizard district (Mullion Island, etc.).

5. Shropshire.[2]

In Shropshire two distinct types of Ordovician are present :—

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[1] The whole series may, however, have been thrust over the volcanic rocks.

[2] C. Lapworth and W. W. Watts, *Proc. Geol. Assoc.*, vol. xiii. (1894) ; W. F. Whittard, *Proc. Geol. Assoc.*, vol. lxiii., 1952, pp. 143-197.

(1) A full sequence of the graptolitic facies (though including some shallow water beds), found on the western side of the Longmynd (Shelve District). Only the higher beds are seen in the Welshpool and Breidden Hills areas.

(2) The shelly facies, which is developed in beds of Bala age, on the eastern side of the Longmynd (type area of the "Caradocian").

(1) West of the Longmynd.

At the base is a hard quartzite (Stiper Stones Quartzite) resting with but slight unconformity on the Cambrian. This is followed by a thick series of shales and flags with many-branched and extensiform graptolites (Arenigian). The Llanvirnian is represented by ashes and shales with the characteristic tuning-fork graptolites (*Didymograptus bifidus* and *D. Murchisoni*), and includes a thick series of andesitic volcanic rocks. The succeeding Llandeilian includes a considerable thickness of calcareous flagstones with *Ogygia buchi, Asaphus tyrannus* and *Trinucleus lloydii,* followed by shales with *Nemagraptus gracilis*. The Caradocian is again of shallower water type, and includes sandstones and shales with a few beds of ash. The Silurian succeeds unconformably, and it is uncertain whether the Ashgillian is represented.

(2) East of the Longmynd.

Here the Caradocian rests unconformably on Cambrian or older rocks. The beds belong essentially to the shelly facies, and comprise grits, calcareous sandstones and shales. Brachiopods (*Orthis alternata, O. testudinaria,* etc.) are abundant, whilst the highest beds (*Trinucleus* Shales) have numerous *Trinucleus concentricus*.

6. The Lake District.[1]

In the Lake District one is approaching the centre of the old Cambrian trough, and, as might be expected, there was continuous sedimentation from the Cambrian

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[1] J. F. N. Green, *Proc. Geol. Assoc.*, vol. xxx. (1919), pp. 153-182; *Ibid.*, vol. xxxi. (1920), pp. 109-126; J. E. Marr, *Geology in the Field* and G. H. Mitchell, *Quart. Journ. Geol. Soc.*, vol. lxxxv. (1929), pp. 38-42; S. E. Hollingworth, *Proc. Geol. Assoc.*, vol. lxv., 1954, pp. 385-402.

into the Ordovician. The upper beds of the Skiddaw Slates have been proved by their graptolites to be of Arenigian age. They are succeeded by a huge series of volcanic rocks—the Borrowdale Volcanic Series — andesites, basalts, rhyolites and tuffs. It should be noted that they do not belong to the typical Spilitic Suite, and are connected with movements of elevation rather than of subsidence. The Lake District rocks are cut by numerous intrusive rocks which comprise:—

a. Microgranites, granophyres and some dolerites associated with the Ordovician vulcanicity.
b. Siluro-Devonian intrusions.
c. Carbo-Permian or Tertiary intrusions.

The intrusions associated with the lavas are slightly younger than them, and are found cutting the Caradocian. Similar intrusions occur also in the Isle of Man, where the Manx Slates are comparable with the Skiddaw Slates.

The main series of volcanic rocks (Llandeilian) were gently folded and denuded before being covered by the deposits of the Caradocian. The latter are known as the Coniston Limestone Series, and comprise sandstones, shales and calcareous beds (with some bands of ash) on the south side of the Lake District; shales on the north.

The succeeding Ashgillian includes limestone, followed by shales, with an extensive trilobite fauna (*Encrinurus sexcostatus, Cheirurus, Ampyx,* etc.).

THE ORDOVICIAN IN SCOTLAND.[1]

The development in the Southern Uplands is of very great interest, in that it exhibits two very distinct facies:

(1) An attenuated succession of shales and radiolarian cherts, the former with numerous graptolites. Type in the Moffat District.
(2) A shelly and trilobitic facies. Type at Girvan (Ayrshire).

In the Girvan area the succession begins with a great thickness of volcanic rocks—typically spilites—which may

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[1] The Silurian Rocks of Britain, vol. i., Scotland (1899), *Mem. Geol. Surv.*

be older than Ordovician. Extensiform graptolites occur in the shales above the volcanic rocks. The Llanvirnian and Llandeilian are represented in the Girvan area[1] by a great thickness of sandstones and greywackes, in the Moffat area by a few feet only of cherts, black shales and mudstones, with the typical graptolites. The Caradocian is represented by 40 feet of mudstones in the south, but by over 1,000 feet of coarse sediments in the Girvan area, the same variation being exhibited by the Ashgillian.

"In the Southern Uplands the replacement of fine sediment by coarse grits, flags, and conglomerates, together with the greatly increased thickness of the divisions when traced in that direction, clearly indicate that the land of the period was situated to the north and west. The extreme thinness of the shales, combined with the presence of radiolarian cherts associated with the very finest sediment, all show that the sea of the period must have sloped very steeply downwards towards great depths[2] along narrow and restricted belts."

THE ORDOVICIAN IN IRELAND.

In the south-east of Ireland is the Leinster Anticline, of which the core is formed by the Leinster granite mass. On both flanks Cambrian, Ordovician and Silurian rocks occur—a continuation of the Welsh Series. In the south of Ireland, Ordovician rocks give rise to little fertile areas where they appear in the middle of domes of old Red Sandstone. In the west, round Killary, Ordovician strata with numerous volcanic rocks occur.

THE ORDOVICIAN VULCANICITY.

A. Extrusive Rocks. These fall into two groups.

1. SPILITIC SUITE. Rocks of this suite are found in areas which were undergoing slow depression. As a whole the rocks are

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[1] It is interesting to note that the *Nemagraptus gracilis* Zone is sometimes represented by the Stinchar Limestone, which has a fauna similar to that of the Derfel Limestone of North Wales, except that the exotic American element is more marked.

[2] Later workers are not agreed that the radiolarian cherts are necessarily very deep water deposits, though laid down in areas comparatively free from terrigenous sediment.

characterized by the high percentage of soda, by the persistent presence of albite felspar and by having a rhombic pyroxene, almost exclusively, as their dark mineral. Rocks of the Atlantic Suite, when sodic, differ in having felspathoids and soda-hornblendes or biotite, whilst in the Pacific Suite olivine appears even in comparatively acid rocks, and is the most marked dark mineral in the basic. The lavas of the Spilitic Suite comprise acid (quartz-keratophyres), intermediate (keratophyres) and basic (spilites or pillow lavas). As areas in which the rocks are typically developed North Pembrokeshire may be cited for the intermediate and Cader Idris for the basic rocks. The more acid magmas of the spilitic suite were very viscous, and explosive action was very pronounced, giving rise to enormous thicknesses of breccia, ashes and volcanic dust. What appear to be massive flows of "rhyolite" or quartz-keratophyre are often beds of very fine recrystallized volcanic dust.

2. Pacific Suite. As mentioned before, folding and faulting, culminating in the great Siluro-Devonian or Caledonian movements, took place at intervals from the Cambrian to the close of the Silurian. Such movements were conspicuous in Lower Bala times—hence the unconformable relationships of the Bala Series to the underlying Volcanic in the Lake District and the pre-Upper Bala age of many intrusions in North Wales. In areas affected by such movements rocks belonging to the Pacific Suite (rhyolites, andesites and basalts) are developed. By their high content of sodium and by the presence of a rhombic pyroxene these rocks show affinities to the Spilitic Suite, and sometimes curiously intermediate, specialized types occur, as at Skomer Island (skomerites, marloesites, etc.). More typically Pacific would appear to be the Lake District rocks.

B. Intrusive Rocks.

There is a large series of intrusions of pre-Upper Bala age, which cut the highest volcanic rocks (*e.g.*, Cader Idris and Lake District), but not the later sedimentary rocks. They are associated with the folding and initiation of faulting which took place at this time. They include mainly :—

1. Granophyres, generally with micrographic intergrowths, but varying greatly in coarseness. They occur both as large masses (summit of Cader Idris; Buttermere and Carrock Fell in the Lake District) and as sills and laccolites. More basic marginal differentiates are frequent.

2. Dolerites ("diabases") are very common all over Wales as small sills and laccolites, often so intimately associated with the volcanic rocks as to leave doubt as to whether one is dealing with a doleritic intrusion or a massive lava. They are essentially rocks with plagioclase and pale augite; olivine and hornblende are absent. More basic and ultrabasic differentiates, either in the lower part of dolerite sills or as separate intrusions (of augite-picrite, etc.), are common both in Wales and the Lake District.

C. Distribution of Ordovician Igneous Rocks.[1]

1. Wales. An attempt has been made to show the distribution of the different types of rock in Wales. This effort (*Fig.* 14) suffers much from lack of recent descriptions of many areas.

2. Lake District. See also map, *Fig.* 27.

3. Isle of Man. Basic dykes occur, cut by acid intrusions.

4. Ireland. Typical spilites occur near Killary (Co. Mayo).

5. Cornwall. Spilites occur in the Lizard area.

6. Ayrshire. Typical spilites occur.

7. Assynt (N.W. Highlands). A plutonic complex of curious rock types occurs here. The intrusions are post-Cambrian, but earlier than the Siluro-Devonian folding.

ECONOMIC GEOLOGY OF THE ORDOVICIAN.

1. Building Stones. Of local use chiefly.

2. Road Metal. The hard Arenig quartzite of the Stiper Stones in Shropshire is a useful road stone, and various grit bands are quarried in parts of Wales, but their use is mainly local. Some of the volcanic rocks, especially the doleritic intrusions, are much quarried both for ordinary road metal and for setts in Wales, especially where they are favourably situated for transport, *e.g.*, along the coast. Some of the Lake District intrusions which may be Ordovician age are extensively quarried, *e.g.*, the Threlkeld Microgranite.

3. Roofing Slates are quarried in various parts of Wales, *e.g.*, in Pembrokeshire (Llanvirnian). Rivalling in importance the Llanberis Slates are those of Blaenau Ffestiniog—black slates at Middle Ordovician. The well-known Green Slates of the Lake District are obtained from volcanic ash-beds of Ordovician Age.

4. Sands. The Stiper Stones Quartzite of Shropshire, when crushed, furnishes a sand of sufficient purity to be used in glass manufacture.

5. Ores. The Lead, Zinc and Barytes veins of Shropshire (Shelve and Middletown) are in Ordovician Rocks, as are also the Leadhills Veins of Scotland.

6. Water Supply. The Ordovician mountains of Wales, the Lake District and Southern Scotland form great catchment areas, and the rainfall is now utilized for the supply of large towns. Reservoirs, both artificial (such as the Vyrnwy Lake, which supplies Liverpool) and natural (such as Thirlmere, which supplies Manchester), are to be found on these Ordovician areas.

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[1] A brief general account of the Ordovician igneous rocks, showing clearly the connexion between rock-types and earth-movements, was given by Prof. A. H. Cox in 1913 (*Rep. Brit. Assoc.*, Birmingham, Section C). The subject was afterwards elaborated by Dr. A. Harker (see references, page 11), but his account is more complicated, as he does not distinguish the Spilitic from the Atlantic Suite.

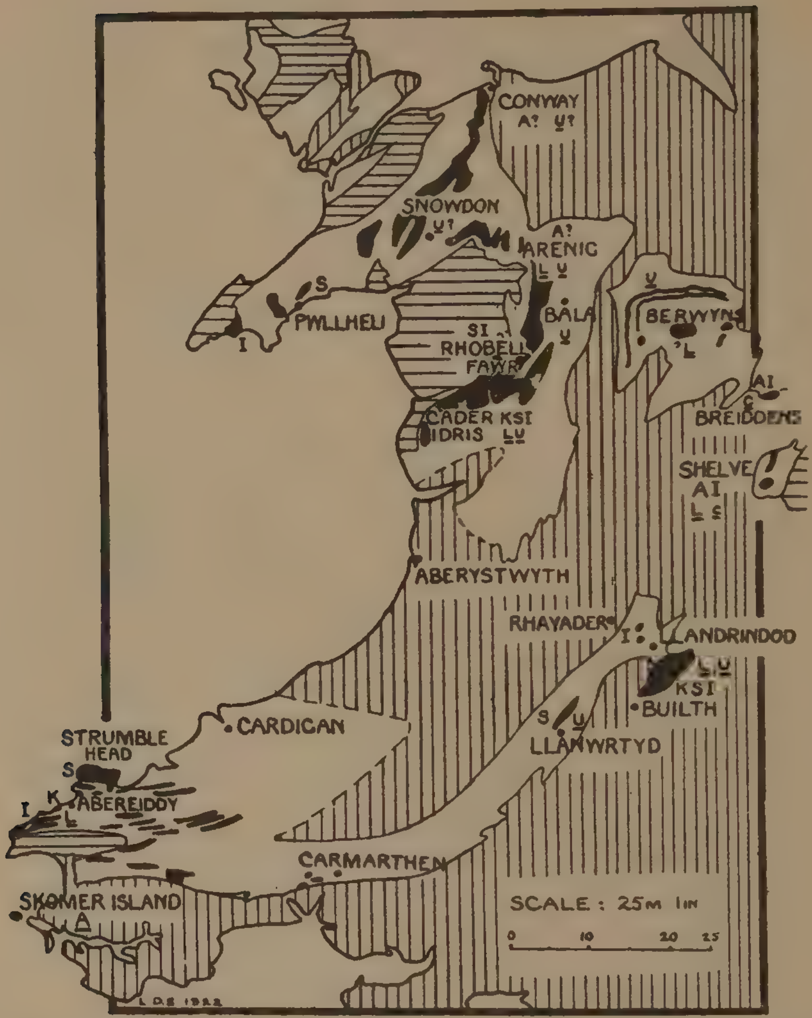

FIG. 14. Map of Wales, showing the Ordovician Volcanic Centres. Horizontal lines = pre-Ordovician; vertical lines = post-Ordovician; blank = Ordovician. Igneous Rocks shown in black; K = Keratophyres; S = Spilites; A = Andesites; I = Intrusions, closely associated with volcanoes; Age of Volcanic Rocks indicated thus, letters underlined in each case: A = Arenigian; L = Llanvirnian; U = Upper Series, *i.e.*, Llandeilo—base Bala; C = Caradocian; *c* = Caradocian ashes only. The outcrops of the igneous rocks are approximate only. (*L.D.S.*)

7. Scenery. The scenery is largely controlled by the resistant masses of volcanic rocks, both lavas and intrusions. The principal mountain ranges of England and Wales consist of Ordovician rocks—the Ranges of Snowdon, Cader Idris, the Arenigs, Plynlimmon, Lake District (Helvellyn), etc. The mountain ranges are often separated by deep valleys—frequently along lines of faults—much modified by glacial action, being long, straight, U-shaped and without spurs. Corrie lakes abound as well as moraine-dammed lakes. Cattle rearing is carried on to some extent in the valleys, which also offer great possibilities of afforestation. The less rugged tracts of Ordovician are heathland or moorland.

LIFE OF THE PERIOD.

The most important members of the Ordovician fauna are Trilobites, Graptolites (branched or biserial) and simple articulate (hinged) Brachiopods. Species are more numerous and varied than in the Cambrian.

a. Arthropoda. All of the three great groups of the Trilobites reach their acme in the Ordovician Period, and towards the latter part especially begin to show curious specialized modifications (*e.g.*, absence of eyes in *Trinucleus*) which herald the slow decline of Silurian times. On the whole they are less spinose than in Cambrian times, the pygidium is larger and often with a broad border. Two of the most characteristic genera are *Trinucleus*, with its large broad-bordered head-shield, and the roughly oval *Asaphus*. The former is restricted to the period. *Trilobites* may be used as zone fossils in beds of " shelly " facies. Amongst others should be noted *Ogygia, Æglina* in the lower part of the series; *Ogygia buchi, Asaphus tyrannus, Agnostus* in Llandeilian; *Trinucleus concentricus, Phacops, Lichas* and *Staurocephalus* in higher beds. Other arthropods are now important, especially ostracods (*Leperditia, Beyrichia* and *Entomis*).

b. Mollusca. Lamellibranchs are not important. Among Gastropods the simple *Hyolithes* remain; *Tentaculites* is important, together with the coiled *Bellerophon*. In the higher beds other coiled forms become important. Simple straight Cephalopods appear, but are rare.

c. Brachiopoda. The horny inarticulate forms are less important. Articulate forms with simple brachial skeletons are important (Orthids and Strophomenids), but spire-bearers, though they appear, are rare.

d. Echinodermata. Cystids and Crinoids are important.

e. Cœlenterata. Graptolites are an extremely important group, and the shaly facies of the Ordovician has been entirely zoned by them. Dendroid graptolites occur, but are not important. Amongst true graptolites certain general characters of stratigraphical importance [1] may be noted :—

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[1] The Graptolites may be considered as falling into a number of main general groups, each of which is characteristic of a definite stratigraphical horizon, and therefore of importance to any field worker. These groups are:—

i. Arenigian. Many-branched forms (*Tetragraptus*), leaf-like forms (*Phyllograptus*) and two-branched forms, in which the branches make an angle of 120° or more with one another ("extensiform graptolites," *e.g.*, *Didymograptus extensus*, *D. hirundo*).

ii. Llavirnian. Two-branched forms, in which the branches make an angle of less than 180° with one another ("tuning-fork graptolites," *e.g.*, *Didymograptus bifidus*, *D. murchisoni*) and simple biserial forms (*i.e.*, with thecæ on both sides of the "stalk").

iii. Llandeilian—especially biserial forms.

iv. Bala. Biserial forms, in which the form of the individual thecæ tends to become more complex, and two-branched forms, which are biserial at first (*Dicranograptus*, *Dimorphograptus*).

Corals, both Rugose and Tabulate, occur, but are not abundant.

f. Porifera. A few doubtful sponges—sphæroidal bodies with a honeycomb-pattern externally (*Ischadites* and *Sphærospongia*)—occur, and also detached spicules of undoubted sponges of various orders.

g. Protozoa. Radiolaria may occur in rock-forming quantities.

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1 The Dendroid Graptolite Fauna—mat-like forms, especially *Dictyonema* (Tremadocian, but ranging up into the Ordovician). True Graptolites are absent in Tremadocian.
2 The Dichograptid Fauna—branched forms, especially two-branched extensiform and tuning fork types (Arenig and Llanvirnian).
3 The Leptograptid Fauna—reclined two-branched forms (Llandeilian).
4 The Diplograptid Fauna—biserial graptolites especially abundant (Bala).
5 The Monograptid Fauna—uniserial unbranched, straight or curved (Silurian).

See G. L. Elles, The Graptolite Faunas of the British Isles. *Proc. Geol. Assoc.*, vol. xxxiii. (1922), pp. 168-200. Dr. Elles has also collected together, in a very succinct and convenient form, lists of the species specially characteristic of each graptolite zone in the Ordovician and Silurian. See *Geol. Mag.*, vol. lxii. (1925), pp. 338-347.

CHAPTER VII.

THE SILURIAN (GOTLANDIAN) SYSTEM.

NAME. The name Silurian (Murchison) was derived from "Siluria," the tract of country once inhabited by the Silures, an ancient British tribe. Rocks of this period are well developed in that area, which may be said to correspond roughly to the Welsh Borderland. Murchison used the term "Silurian System" long before the lower limits of the system were defined. He worked downwards from the base of the Old Red Sandstone, whereas Sedgwick, with his "Cambrian System," was working upwards from the oldest rocks. A long controversy as to the delimitation of the two systems ensued. It was terminated by a recognition of an intermediate (Ordovician) system, but for a considerable time the Ordovician and Silurian were called respectively Lower and Upper Silurian. For that reason some authors prefer the name "Gotlandian" (from the Island of Gotland) for the system here called "Silurian." Gotlandian is a bad name, as the sequence in Gotland is still very imperfectly understood, and probably includes rocks which are really of Devonian Age.

GEOGRAPHY OF THE PERIOD.

1. For the purpose of a preliminary account the Silurian may be divided into :—

c. Ludlovian or Ludlow Series.
b. Wenlockian or Wenlock Series.
a. Valentian or Llandovery Series.

2. Speaking generally the conditions during Silurian times resembled those of Ordovician times. There were certain important differences, however.

a. Volcanic activity had practically ceased. It was prolonged into the Valentian in a few areas only (even later in Ireland).

b. There was renewed "buckling" of the old geosyncline, and, especially towards the end of the period, the basins of deposition became almost entirely filled up. Whilst in the Valentian there is, as in the Ordovician deposits, a well-marked contrast between the shaly graptolitic facies (deposited in the centre

of a trough) and the calcareous shelly facies (deposited towards the margins of the trough and comprising conglomerates, sandstones, etc.); the distinction is less obvious in the higher series, and almost disappears in the higher Ludlovian, where graptolites themselves disappear.

3. The end of the Ordovician was marked by gentle folding, and the sediments were thrown into a series of puckers. There was one well-marked trough from Wales to the Lake District, and in the centre of this synclinal hollow the earliest Valentian sediments follow conformably, and it may be almost impossible to define their base. Elsewhere there is an unconformity at the base of the Valentian, and the lowest beds are often absent.

4. Similar small movements occurred in the middle of the Valentian, so that the Upper Valentian often rests unconformably on the Lower and overlaps it. The overlap indicates pronounced submergence.

5. In Wenlockian times the contrast between the shelly and graptolitic facies is accentuated to a slight extent by the presence of coral reefs and shallow water limestones towards the shorelines. The graptolitic rocks are, however, of shallower water type, and have many other fossils. Some intra-Silurian local movements can sometimes be traced (as near Builth).

6. The final silting up of the Old Cambrian geosynclinal trough is evidenced by widespread deposits of calcareous mudstone and sandy beds in the higher part of the Ludlovian.

7. The history of the Silurian, then, recapitulates that of the Ordovician—numerous small movements took place along the old Cambrian trough and folds running S.W.—N.E. were the result. These movements culminated in the great Caledonian folding, which brought the period to a close. The structure of Wales (illustrated in the map, *Fig.* 25 and section *Fig.* 26) is mainly due to Caledonian folding, but was outlined at an earlier date and completed during the Carbo-Permian period of folding.

NOTE.—A classification of the Silurian which has been largely adopted is into three divisions—

c. Downtonian = post-Aymestry Limestone.
b. Salopian = Woolhope Limestone to Aymestry Limestone inclusive.
a. Valentian.

The close of the Salopian is marked by the disappearance of the last graptolite in England. The upper limit of the Silurian System is a matter of dispute, and reasons are given below (p. 117) for considering the bulk of the "Downtonian" as Devonian, and, as there is no break at the top of the "Salopian," the old divisions of Wenlock and Ludlow are much more convenient.

THE SILURIAN IN GREAT BRITAIN.

I. Valentian or Llandovery Series.

The series may be divided into two stages :—

b. Upper = Upper Llandovery (shelly facies) or Gala (graptolitic facies).
a. Lower = Lower Llandovery (shelly facies) or Birkhill (graptolitic facies).

In several localities in Wales the Upper Llandovery consists of calcareous or arenaceous beds in the lower part and shales in the upper part. The latter were formerly believed to be on a definite horizon and were called the "Tarannon Shales."

From what has been said above with regard to the folding in late Ordovician times, it follows that the Lower Valentian rocks are much more restricted in their distribution than are the Upper.

An attempt has been made, by means of a sketch map (*Fig.* 15) to show the distribution of the different facies of Llandovery rocks.[1] It will be noticed

a. That there is a broad band, having a roughly Caledonian (N.E.-S.W.) trend, along which the whole series is graptolitic and practically complete. The base of the Valentian is marked by only a faunal break or by a slight discordance. (The latter is shown by a wavy line in *Fig.* 15.)
b. That there is a band on either side along which the sequence is shelly or mixed, but still fairly complete. There is usually a break at the base.

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[1] O. T. Jones, "The Valentian Series," *Quart. Jour. Geol. Soc.*, vol. lxxvii. (1921), pp. 144-174.

FIG. 15. Map showing the distribution of Valentian deposits in Great Britain. (*L.D.S.*)

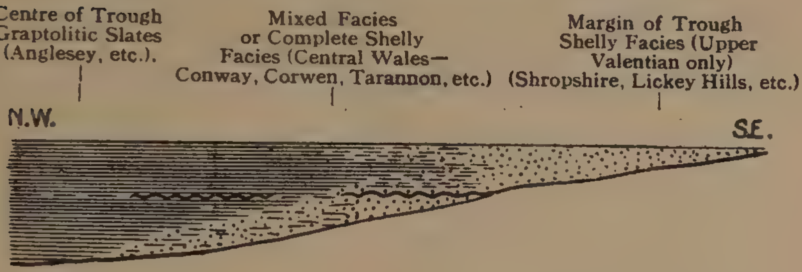

FIG. 16. Diagrammatic Section from the Centre to the margin of the Valentian Trough. The wavy line indicates the local unconformity between the Upper and Lower Valentian. (*L.D.S.*)

c. That to the south-east is a belt where only the Upper Valentian is present. This region falls into two sub-areas—

(i) One characterized by *Stropheodonta compressa,* and in which contemporary volcanic rocks are present.

(ii) The other characterized by *Pentamerus oblongus.*

d. That an unconformity, of varying importance, separates the Upper and Lower Divisions over the greater part of the central belt, especially where the shelly facies prevails. This unconformity is shown in *Fig.* 15 by a wavy line separating the letters U and L; an arrow indicates a gradual passage, without discordance.

1. THE GRAPTOLITIC FACIES is found in the centre of the old trough. The rocks of this facies are best seen in North Wales, Anglesey (the higher beds have been removed by denudation), the Lake District and the Moffat area of Southern Scotland (Upper Valentian is here sandy). The base is either marked by an abrupt change of fauna, or by a change in lithology. The total thickness of the graptolitic facies, as with deep-water deposits in general, is very slight when compared with the shelly facies. The rocks have been divided into a number of graptolite zones; *Glyptograptus persculptus* characterizes the lowest, followed by a zone of *Diplograptus acuminatus*, but monograptids are the characteristic fossils of the bulk of the series. In the Lower Valentian *Monograptus cyphus* and *M. spinigerus* may be mentioned; in the Upper, *M. crispus*, *M. crenulatus* and *Rastrites maximus.* The Lower and Upper Valentian are called Birkhill and Gala Beds respectively in Scotland and Skel-

gill and Browgill Beds in the Lake District.[1] Among trilobites *Ecrinurus punctatus* and *Phacops glaber* are important in the Skelgill Beds. Remains of organisms belonging to other groups are rare.

2. THE MIXED FACIES along the Northern belt is well displayed at Girvan, along the Southern near Corwen, etc.

3. THE SHELLY FACIES is seen fairly complete at Haverfordwest, Llandovery and near Rhayader, but is especially fossiliferous in the two first-mentioned localities. Great thicknesses of coarse conglomerates are often present. The graptolitic facies ("Tarannon Shales") often invades the higher part of the sequence as at Tarannon. *Atrypa marginalis*, *Stricklandinia lens* and *Plectambonites duplicatus* characterize the Lower Llandovery; *Stricklandinia lirata*, *Pentamerus oblongus* and *Stropheodonta compressa* the Upper. Besides brachiopods, corals, lamellibranchs, gastropods, cephalopods and trilobites are common.

4. MARGINAL AREAS (Upper Llandovery only).[2]—The southern part has *Stropheodonta compressa* as a typical fossil. Basic volcanic rocks are developed in Pembrokeshire, the Tortworth and Mendip Inliers. The northern part, which includes the Shropshire districts, has *Pentamerus oblongus*. There is usually a conglomerate or shelly sandstone at the base. The Upper Llandovery may rest on any rocks from Pre-Cambrian upwards. It is interesting to compare the development in North-West Ireland, where the Valentian is represented by coarse sandstones. In parts of Mayo and Galway the Valentian rests on Pre-Cambrian.

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[1] The Skelgill and Browgill Beds together form the Stockdale Shales (Valentian). A very interesting study has been made by J. E. Marr, Conditions of Deposition of the Stockdale Shales of the Lake District, *Quart. Jour. Geol. Soc.*, vol. lxxxi., 1925, pp. 113-136. It is quite clear that the beds were "deposited in still waters away from the coastal belt." See also note under *Fig.* 17.

[2] Reference should be made to the interesting studies of the Valentian shore deposits of Shropshire made by Dr. W. F. Whittard, *Quart. Jour. Geol. Soc.*, vol. lxxxviii., 1932, pp. 859-902.

5. Valentian rocks may be present in the extreme south of Devon and Cornwall, they certainly occur in Brittany. The graptolitic Upper Valentian rocks found in the Chilham Boring (Kent) belong to the Brittany-Ardennes province.

A rough indication of the geography of the period has been shown on Fig. 15 (inset).

II. Wenlockian or Wenlock Series and
III. Ludlovian or Ludlow Series.

These beds were laid down in a trough which corresponds roughly with that in which the Valentian was deposited, and it is unnecessary to illustrate the area by another map. The conditions were, however, somewhat different.

a. The contrast between the graptolitic and shelly facies is less marked, and a large number of organisms are common to both. The shallow water limestones of the shelly facies tend, however, to make the two facies more distinct.

b. More precisely the centre of the trough was being silted up by muds and sands in which the last of the graptolites are buried. Along the sides of the trough the water was sufficiently clear to permit the growth of coral reefs at certain times. This indicates that the lands fringing the sea had been worn down and yielded little sediment. At other times calcareous shales—often with graptolites—were laid down.

The relation between the various beds may best be shown by means of a diagrammatic section from north north-west to south south-east, obliquely across the trough.

1. CALCAREOUS (SHELLY) FACIES. This is most typically developed in Shropshire, the Woolhope Inlier (Herefordshire), etc.

THE WOOLHOPE LIMESTONE is a dark blue flaggy limestone with a fauna closely allied to that of the succeeding shales. *Illænus barriensis* is one of the most typical fossils. At Old Radnor the limestone rests directly

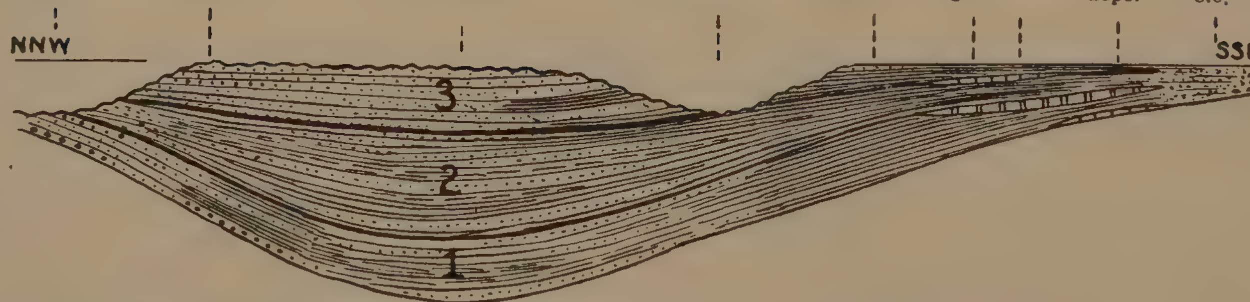

FIG. 17. Diagrammatic Section obliquely across the Wenlock-Ludlow Trough of Deposition. 1, Wenlock Series; 2, Lower Ludlow Series; 3, Upper Ludlow Series. Compared with the thicknesses shown elsewhere, that in the Lake District should be greatly increased. As shown by the wavy line, the higher deposits have been removed by denudation in many areas. (*L.D.S.*)

Professor J. E. Marr has made a special study of the conditions of deposition in the Lake District and traces changes due to variations in depth of the water, distance from the coast lines, etc. He concludes that open water conditions prevailed in Valentian and Wenlock times, shallower conditions in Ludlow times, actual coastal conditions appearing in Upper Ludlow times. See *Geol. Mag.*, vol. lxiv., 1927, p. 500.

on Pre-Cambrian, and has been built up to a considerable extent by calcareous algæ (*Solenopora gracilis*).[1]

THE WENLOCK SHALES are calcareous mudstones with certain bands very rich in small brachiopods. These brachiopod beds are particularly well developed about the middle (Buildwas Beds), and at the top of the shales (Tickwood Beds), other horizons being barren. *Orthis* (*Dalmanella*) *elegantula, O. elegantulina, O. hybrida, Bilobites biloba* (Buildwas Beds) *O. rustica, Plectambonites transversalis* are common brachiopods.

THE WENLOCK LIMESTONE has assumed an exaggerated importance on account of the beauty and variety of its fossils. In places it is largely built up of corals in the position of growth,[2] elsewhere brachiopods (*Atrypa reticularis, Meristina tumida, Leptæna rhomboidalis*), trilobites (*Calymene blumenbachi, Dalmanites caudatus*), lamellibranchs and crinoids (*Actinocrinus*) are important. The corals include *Acervularia, Omphyma* and numerous tabulate corals. The limestone is well developed round Wenlock and at Dudley, to the west and south-west it passes rapidly into shales.

THE LOWER LUDLOW SHALES contain many of the fossils of the Wenlock Shales and Wenlock Limestone. *Cardiola interrupta* is a typical lamellibranch. In the upper part is a famous "Starfish Bed." These shales often have a nodular structure.

THE AYMESTRY LIMESTONE is more local than the Wenlock Limestone. It is thickest at Aymestry (near Ludlow), and is considerably attenuated where the Wenlock Limestone attains its maximum. It is often built up largely of the brachiopod *Conchidium knightii*, elsewhere *Atrypa reticularis, Dayia navicula, Wilsonia wilsoni* or *Strophomena euglypha* may predominate. Partly overlying the limestone and partly forming its lateral equivalent are the calcareous Mocktree Shales. These yield a fauna similar to the Aymestry Limestone, and in them is found the last English graptolite, *Monograptus leintwardinensis*. *Dayia navicula* is especially abundant.

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[1] E. J. Garwood and E. Goodyear, *Quart. Jour. Geol. Soc.*, vol. lxxiv. (1918), pp. 1-30.

[2] M. C. Crosfield and M. S. Johnston, *Proc. Geol. Assoc.*, vol. xxv. (1914), pp. 191-228.

THE UPPER LUDLOW SHALES[1] are massive, blue, calcareous flagstones, becoming nodular or thinly - bedded in the upper part. In the lower half *Camarotoechia nucula* is abundant, in the higher half *Chonetes striatella*. Lamellibranchs such as *Orthonota* become abundant.

To the south and south-east the Wenlockian and Ludlovian become more sandy and imperfectly developed, showing the near proximity of a shoreline (Tortworth and Cardiff).

2. NON-CALCAREOUS (GRAPTOLITIC) FACIES. — The accurate delimitation of the Wenlockian and Ludlovian (at no time well marked) has really only become possible by the use of graptolite zones.[2] The Wenlockian is divisible into six zones, based principally on species of *Cyrtograptus*; the Ludlovian into five,[3] based on species of *Monograptus*. Only *Monograptus* and *Retiolites* survive into the Ludlovian. A few brachiopods, trilobites, lamellibranchs, etc., are found in the graptolitic shales, but they are mostly small. Although the Wenlockian and Ludlovian form a monotonous series of more or less homogeneous shales, the local absence of certain zones seems to indicate slight movements during the deposition of the beds. Even in the typical districts for the argillaceous or graptolitic facies the Upper Ludlovian tend to become sandy and coarser, giving evidence of the final silting up of the old trough. Among typical graptolites of the Wenlockian may be mentioned *Cyrtograptus murchisoni*, *C. linarssoni*, *C. lundgreni*, *Monograptus priodon*. In the Ludlovian *Monograptus vulgaris*, *M. scanicus*, *M. colonus* and *M. leintwardinensis* are typical. The graptolitic facies is typically developed in Wales—Builth and Long Mountain (mudstone), also Denbighshire[4] (flags, etc.)—and the Lake District (flags, etc.).

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[1] G. L. Elles and I. L. Slater, *Quart. Jour. Geol. Soc.*, vol. lxii. (1906), pp. 195-222.

[2] G. L. Elles and E. M. R. Wood, *Quart. Jour. Geol. Soc.*, vol. lvi. (1900), pp. 370-414 and 415-492.

[3] Graptolites are absent in the Upper Ludlovian.

[4] But even here, towards the centre of the trough, definitely shallow water. See P. G. H. Boswell, *Quart. Jour. Geol. Soc.*, vol. lxxxii. (1926), p. 583.

In the Southern Uplands this facies, passing up into coarse beds, is developed to the south and south-east; to the north-west (Girvan) the shelly facies, with sandstones and conglomerates, is developed. From the diagram the huge thickness of the beds in the Lake District is readily apparent (about 14,000 feet), and also the great area covered by sandy flagstones rather than shales.

Silurian rocks are known from several borings through the Mesozoic cover of South-eastern England. The Wenlockian and Ludlovian there, as the Valentian, probably belong to the Brittany-Ardennes area of deposition.

THE SILURIAN IN IRELAND.

Still very imperfectly known but one of the most important features is the presence of volcanic rocks in the south-west in County Kerry. A great volcano appears to have been in activity as late as Lower Ludlow times. The presence of littoral beds towards the old northern shore in the north of County Galway may be noted.

ECONOMIC GEOLOGY OF THE SILURIAN.

1. Building Stones. Not very important. The limestones are used locally.

2. Road Metal. Important locally, especially the limestones.

3. Lime and Cement. The various beds of Limestone, especially the Wenlock Limestone, have been extensively quarried for lime. The escarpment of Wenlock Edge is riddled with quarries from end to end. Where the limestone occurs as inliers in industrial districts, notably at Dudley, it has been much used as a flux in the iron-smelting industry.

4. Roofing Slates. A small industry in the Lake District.

5. Water Supply. The extensive tracts of Silurian Rocks, like the Ordovician, form important gathering grounds for rainfall. The water is utilized for the supply of great towns (Elan Lake, near Rhayader, on Valentian, supplies Birmingham).

6. Scenery and Industries. The areas of Silurian strata vary greatly in this respect. The non-calcareous facies, especially where folded and cleaved, forms barren mountainous tracts like the Ordovician (Central Wales). Where the whole series is slightly calcareous and little altered cultivation is extensive (Clun Forest). In the typical regions of the calcareous facies (Shropshire, Woolhope Inlier, etc.), the limestones give rise to escarpments — of which the scarp slopes are thickly wooded—separated by fertile valleys, which mark the outcrop of the shales.

LIFE OF THE PERIOD.

The most important members of the Silurian fauna are uniserial Graptolites (*Monograptus*), Trilobites and Articulate Brachiopods (more varied and complex than in the Ordovician). Corals and Crinoids are also abundant.

a. Arthropoda. Most of the families of Trilobites present in the Ordovician persist (with the exception of the Trinucleidæ and the Asaphidæ). Some of the most typical genera are *Calymene, Phacops, Encrinurus,* and *Lichas.* Many of the genera exhibit bizarre features characteristic of incipient decadence — spinous characters in *Lichas* and *Acidaspis,* huge glabella in *Deiphon.* practical loss of three-fold longitudinal division in *Homalonotus,* wide glabella in *Cheirurus.* Amongst other Arthropods, Ostracods (*Beyrichia*) often swarm in huge numbers; there are "shrimp-like" *Ceratiocaris;* still more characteristic towards the end of the period are Eurypterids (*Eurypterus* and *Pterygotus*).

b. Mollusca. Lamellibranchs become abundant, especially forms with hingeless valves, which, in the absence of teeth, are difficult to classify and of little use in Stratigraphy (*Cardiola, Ctenodonta, Orthonota, Pterinæa* and *Modiolopsis*). Gastropods are more varied, but, with the exception of *Murchisonia* and one or two others, have simple (homostomatous) mouths. *Pleurotomaria, Bellerophon,* the much-wrinkled flattened *Omphalotrochus,* and *Hollopella* may be noted. Cephalopods are numerous, but all belong to the Nautiloidea, and are straight (*Orthoceras*), curved or inflated (*Gomphoceras, Cyrtoceras,* etc.).

c. Brachiopoda. Most of the Ordovician genera persist, and more complex articulate forms appear. The Pentamerids attain their acme (*Pentamerus, Conchidium*). The Spiriferacea, with their complex spiral brachial skeletons, are particularly interesting (*Cyrtia, Cyrtina, Meristina* and *Atrypa*). Rhynchonellids first appear (*Camarotœchia* and *Wilsonia*).

d. Polyzoa are often present in rock-forming numbers (Wenlock Limestone).

e. Echinodermata. Cystids continue to be common; the earliest Blastoid (*Codaster*) appears: more important are the abundant limestone forming crinoids. The earliest Echinoid appears in the Ordovician, but the group is not yet important in the Silurian. Some interesting starfish occur.

f. Cœlenterata. Graptolites are again extremely important as zonal fossils, and they die out with the Silurian. They are uniserial forms, either straight (*Monograptus*) or curved and slightly branched (*Cyrtograptus*) or loosely coiled (some *Rastrites*). Both Rugose and Tabulate Corals become very important as rock-formers (*Cyathophyllum, Omphyma, Cystiphyllum* and *Acervularia* among the former, *Favosites, Halysites* and *Heliolites* among the latter).

g. Porifera—as in the Ordovician.

h. Protozoa. Radiolaria are important, but Foraminifera still exceedingly rare.

CHAPTER VIII.

THE SILURO-DEVONIAN EARTH-MOVEMENTS AND THE DEVONIAN SYSTEM.

THE SILURO-DEVONIAN EARTH-MOVEMENTS.

The close of the Silurian was marked by a succession of very important earth-movements. These are most in evidence in the north of Scotland, and to a gradually lessening degree towards the south. The physiography of the whole of the region north of a line drawn from the middle of the west coast of Ireland to the Tweed may be said to be controlled, even at the present day, by this great series of South-west—North-east or "Caledonian" folds. Like all great folding movements, they neither commenced suddenly nor were restricted to one short period of time. The direction of the folds corresponds roughly with that of the long axis of the Silurian basins of deposition, and is thus connected with the crumpling of the old Euro-American trough of Cambrian times. The period of greatest movement was probably at the end of the Silurian, but movements along the same lines took place at intervals during the Devonian period. The great movements at the end of the Carboniferous, though usually associated with east-west or north-south folds in other parts of the country, seem to have accentuated existing folds in those regions affected by the Caledonian movements. Even at the present day most of the frequent earthquakes of Scotland are associated with the great faults of Caledonian trend. As far as the British Isles are concerned, Scotland may be described as the "storm centre" of the Caledonian folding. In the North of England and in North Wales—and probably also in the Midlands of England—the movements were still very important. In the South, however, the most marked effect of the movements was the formation of an

east and west ridge from South Wales, probably under the London District, to Belgium.

GEOGRAPHY OF THE DEVONIAN PERIOD.

To the north of a line running approximately from the Bristol Channel to Belgium, the British Isles formed part of the great Devonian Continent of Northern Europe; to the south of this line marine conditions for the most part prevailed. The deposits of the Devonian Period fall, therefore, into two types or facies :—

1. The **Old Red Sandstone** or **Continental Type,** deposited in the mountain-girt depressions between the main ranges.

2. The **Devonian** or **Marine Type,** restricted in the British Isles to Devon, Cornwall and Somerset, but having a wide distribution on the Continent of Europe—in North France, Belgium, Germany, etc.

THE DEVONIAN MOUNTAINS.

The following main ranges, all of which strike from north-east to south-west (see map, *Fig.* 18) may be distinguished :—

1. The **North-West Highlands of Scotland.**

2. The **Central Highlands.**

3. The **Southern Uplands,** passing across into Ireland.

4. The **North Wales Mountains**; almost certainly extending across to the south-eastern corner of Ireland, and possibly also to the Lake District.[1]

In addition there was to the south

5. The **low but important ridge** from Ireland, by

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[1] It should be noted that the Carboniferous Sea penetrated from the west *between* North Wales and the Lake District, for that reason the hills of the Lake District and North Wales probably formed two parallel ranges with a marked valley between, as shown in *Fig.* 18.

the Bristol Channel to Belgium (note that the direction is approximately west to east in this case).[1]

Like the complexity in folding, the mountains decreased in elevation from north to south. The Range of the North-West Highlands must have rivalled in grandeur and elevation the Alps of the present day.

FIG. 18. The Geography of Early Devonian Times. Existing Devonian outcrops in black.

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[1] Later work seems to indicate that this ridge did not emerge above sea level—at least in early Devonian times. See A. Heard and R. Davies, *Quart. Jour. Geol. Soc.*, vol. lxxx., 1924, pp. 513-514 and 516-519. But the question is far from settled and the contrary view is expressed by D. M. Williams, *Geol. Mag.*, vol. lxiii., 1926, pp. 219-222.

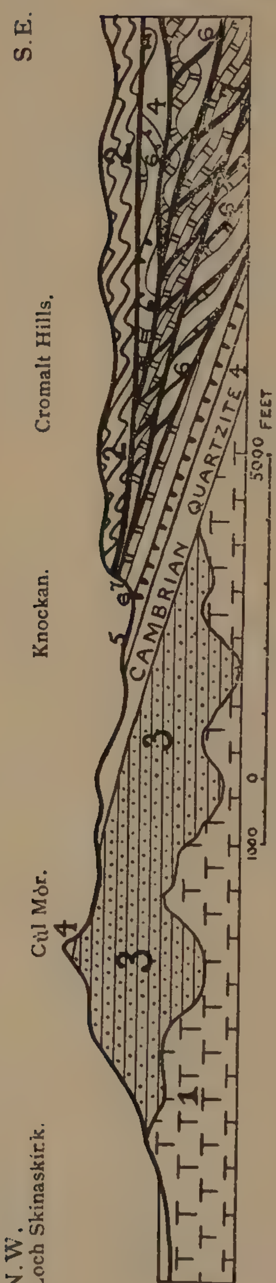

FIG. 19. Section across the North-West Highlands, showing the structure and the disposition of the Cambrian and Pre-Cambrian Strata. 1, Lewisian; 2, Moinian; 3, Torridonian; 4, Basal Cambrian Quartzite; 5, Pipe Rock; 6, Fucoid Beds and Serpulite Grit; 7, Durness Limestone. (*L.D.S.*)

THE STRUCTURE OF THE DEVONIAN MOUNTAIN RANGES.

1. The North-West Highlands.[1]

Here the results of Caledonian folding may be summarized as follows :—

a. The rocks have everywhere been thrown into a series of isoclinal folds, which are bent over towards the north-west.

b. The rocks have frequently given way under the intense strain, and reversed faults and thrusts take the place of folds. The thrusts form two series, major thrusts and minor thrusts.

c. The main effect of the major thrusts has been that

(i) Lewisian with Cambrian strata appear to be driven westwards over the Lewisian gneisses and Cambrian rocks.

(ii.) These displaced masses are in turn covered by great slices of Lewisian gneiss, often with overlying Torridonian and Cambrian strata.

(iii.) Finally sheets of the Eastern Schists have ridden right over the whole, and often come to rest directly on Cambrian or on the gneisses of the fundamental complex (Lewisian).

Certain of the thrust masses are in turn riddled by small thrust planes[2] ("imbricate structure"). The diagrammatic section (*Fig.* 19), simplified from an actual section, should make this structure clear.

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[1] B. N. Peach and J. Horne, *op. cit.*

[2] Or reversed faults. They are older than the main thrusts.

d. Incidentally the rocks have developed new schistose structures, and some bands are entirely broken up and recrystallized (*i.e.*, mylonized).

A considerable difference of opinion exists concerning the forces which produced these structures.

a. At first sight it would appear that both the isoclinal folding and the thrust faulting have been produced by a powerful pressure from the south-east crushing the strata against a resistant mass or "stable block" of the earth's crust somewhere in the north-west. This is illustrated diagrammatically in *Fig.* 20.

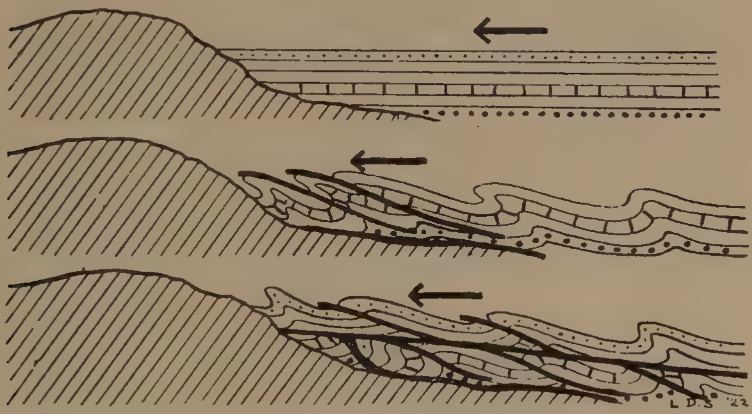

FIG. 20. Diagrams to illustrate the development of thrusts by pressure against a stable block. (*L.D.S.*)

Would the folds increase in intensity towards the direction from which the pressure came (*i.e.*, towards the south-east), or towards the "stable block"? The former seems more likely as the simple experiment of pushing a mass of some kind against a pile of sheets of paper will show. But the folds in Scotland *decrease* in intensity towards the south-east.

b. Another explanation is possible. One can conceive a huge block of the earth's crust being moved, by some great internal movements, *against* a comparatively weak series of sedimentary strata. This is illustrated in *Fig.* 21.

It is claimed by some that this would account for the folds dying away to the south-east in Scotland.

c. Some geologists claim that such structures can be produced by equal pressure in two directions, or rather that unilateral thrust cannot exist in the earth's crust parallel to the surface. It seems more likely, however, that given equal pressure in two directions an ordinary anticlinorium or synclinorium would be produced, as shown in *Fig.* 22.

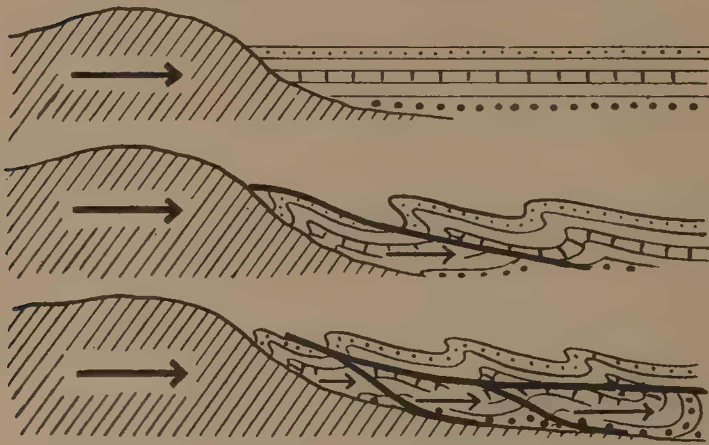

FIG. 21. Diagrams to illustrate the development of thrusts by "underriding." (*L.D.S.*)

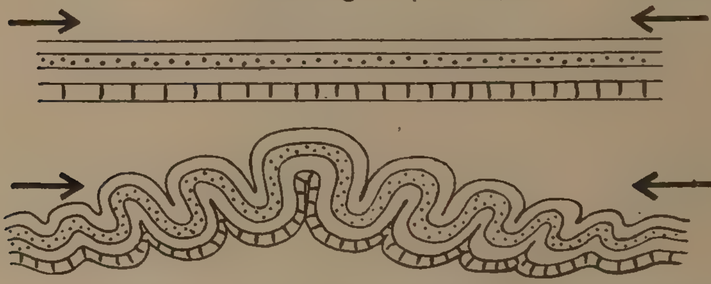

FIG. 22. Formation of an Anticlinorium by equal pressure in opposite directions. (*L.D.S.*)

2. The Grampians or Central Highlands.

The structure of the Central Highlands is still very imperfectly understood.[1] They are much folded, in an apparently irregular fashion, into isoclinal folds, which may slope either towards the north-west or the south-east, but the main "grain" of the country is clearly Caledonian. Huge thrusts, if such exist, have yet to be located with certainty, though examples have been described in the south-west, where a strong case for their existence has been made out by Professor E. B. Bailey. There are numerous faults, but apparently of ordinary normal or reversed types. The following points may be noted :—

a. The presence of numerous intrusive masses of the older

[1] The Pre-Cambrian age of the folding of comparable rocks in Anglesey has recently been demonstrated, and it is quite possible that a great part of the folding of the Central Highlands is also Pre-Cambrian.

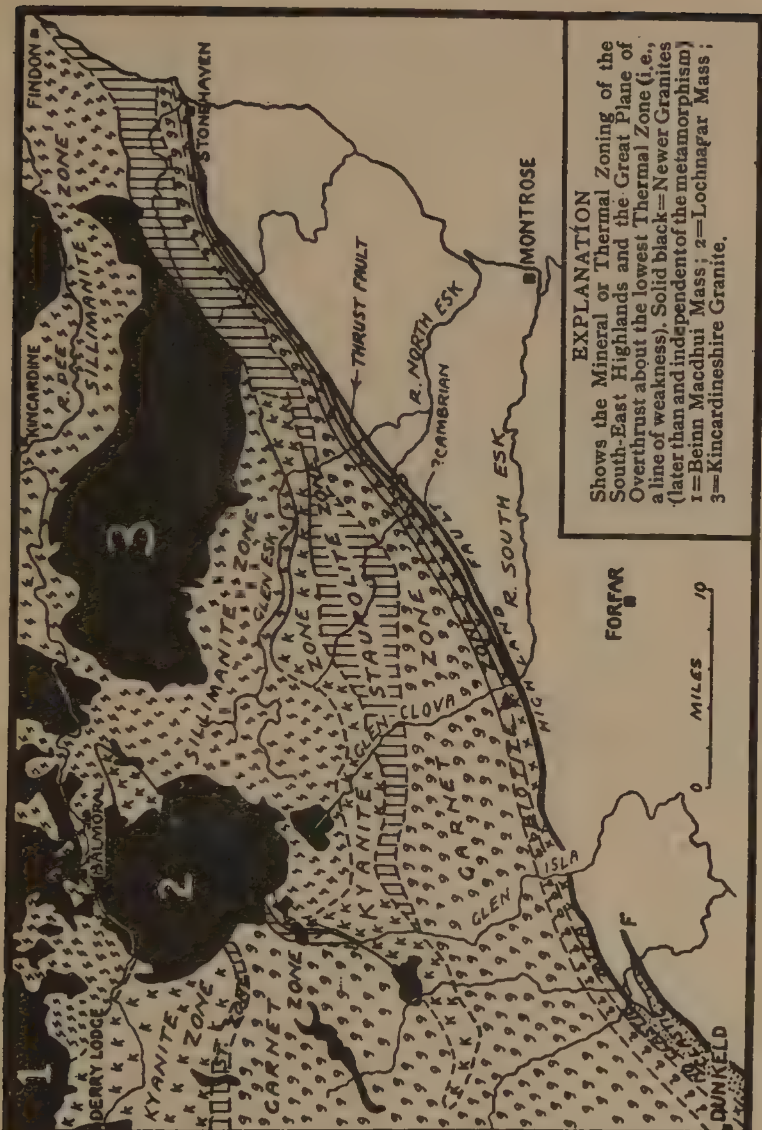

FIG. 23. Sketch Map of part of the S.E. Highlands. (After *G. Barrow.*) More recently Prof. C. E. Tilley has examined the metamorphic zones especially in the region to the south-west of this map and is unable to agree with Mr. Barrow. He finds the sequence *inverted* and his interpretation lends support to Prof. E. B. Bailey's interpretation of the structure (p. 44 above). See *Quart. Jour. Geol. Soc.*, vol. lxxxi., 1925, pp. 106-109.

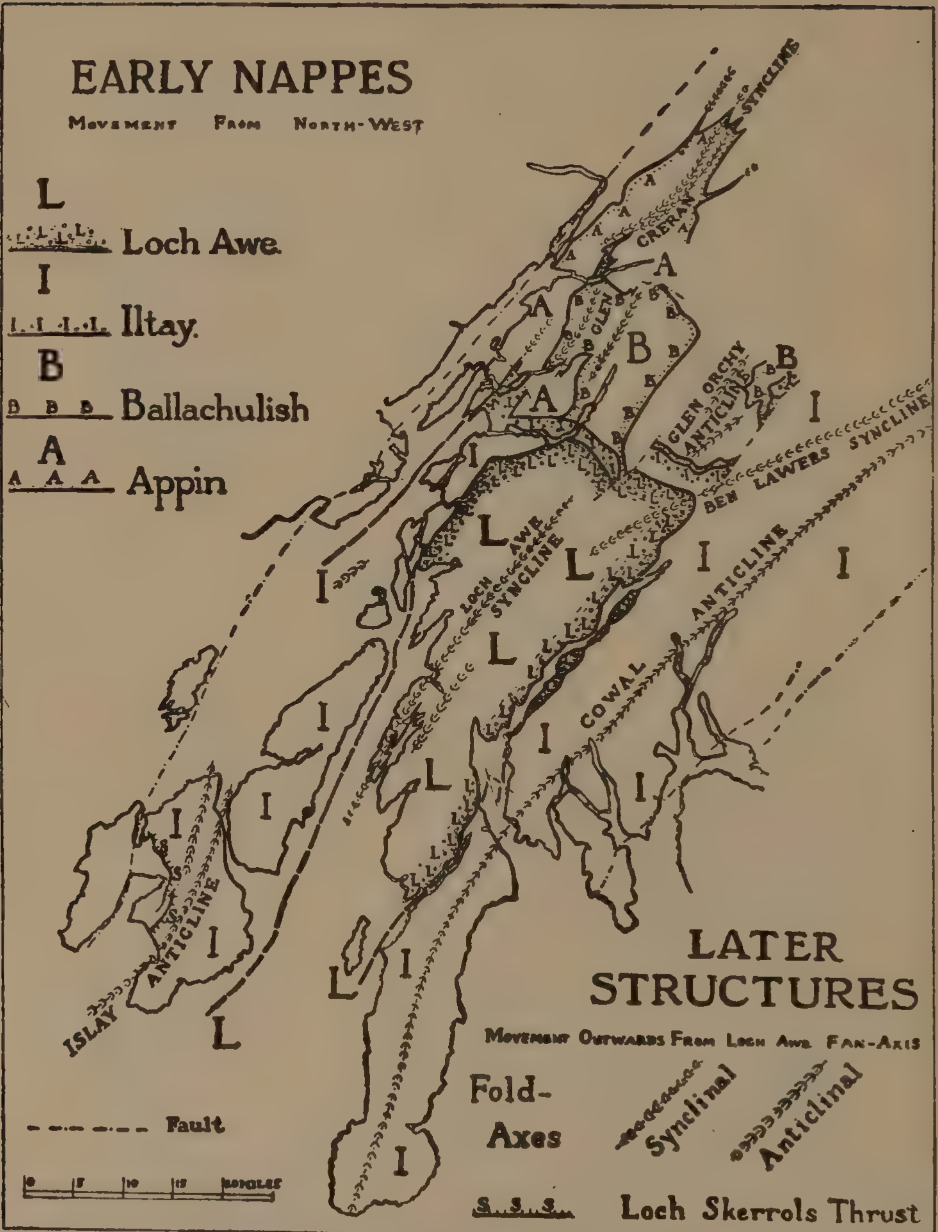

FIG. 23a. The nappes (faulted limbs of recumbent overfolds) of the South-West Highlands according to Prof. E. B. Bailey. (*Reproduced by permission of the author and of the Council of the Geological Society.*)

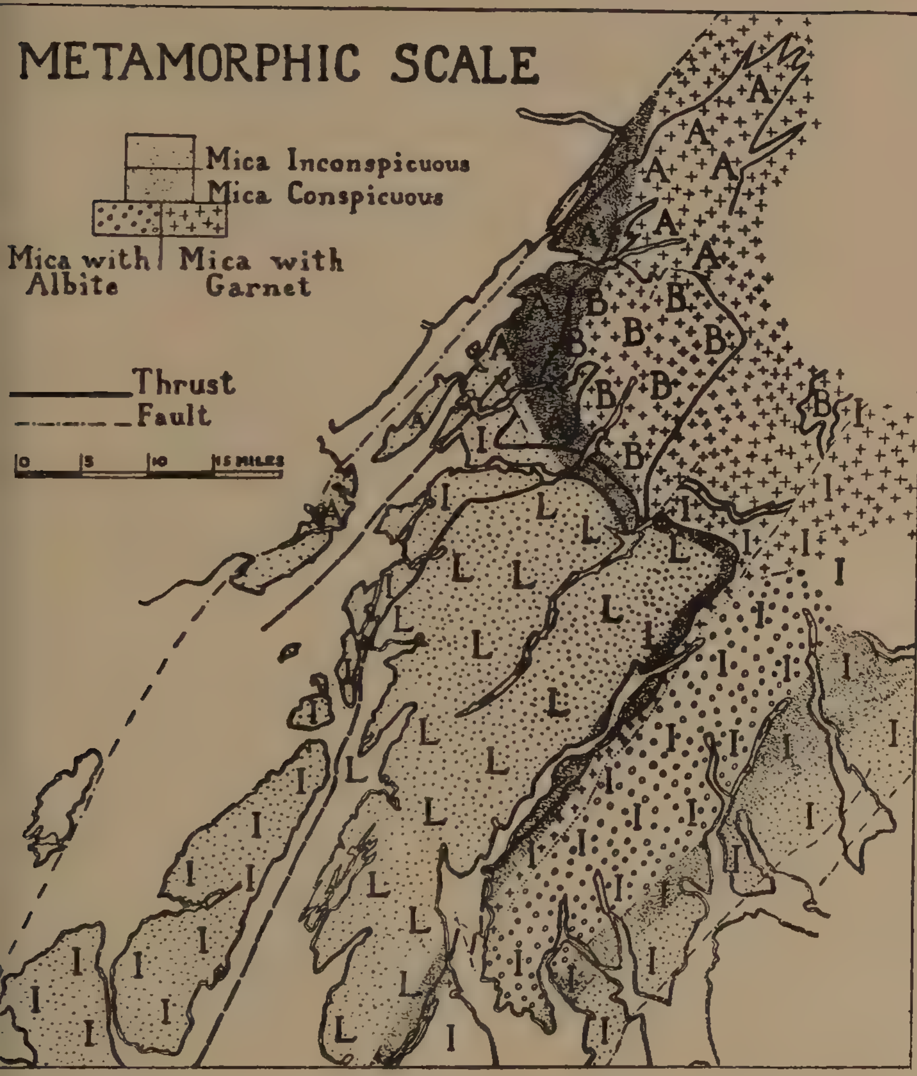

FIG. 23b. The Metamorphic Scale of the South-West Highlands according to Professor E. B. Bailey. The letters refer to the nappes shown on *Fig.* 23a. (*Reproduced by permission of the author and of the Council of the Geological Society.*)

(?Pre-Cambrian) granites may have made the whole area more resistant to folding.

b. The folding which did take place may have been partly obliterated by the intrusion of the newer granites and later intrusions.

c. Mr. G. Barrow[1] claims that the structure becomes quite simple if one considers the area as one of progressive dynamic metamorphism. The centre is most highly altered, and is surrounded by roughly oval bands of gradually less altered rocks. Each "zone" of metamorphism is characterized by some particular mineral. These thermal zones, from the centre outwards, are :—

i. Sillimanite zone.
ii. Kyanite zone.
iii. Staurolite zone.
iv. Garnet zone.
v. Biotite zone.
vi. Zone of digested clastic micas.

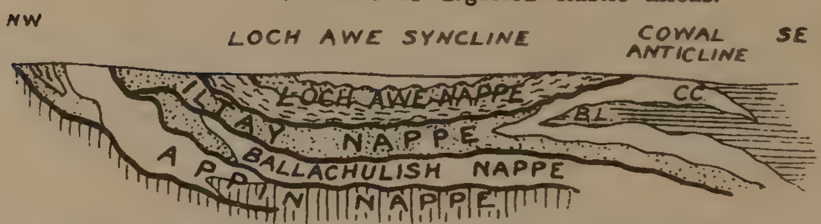

FIG. 23c. Diagrammatic Section through the Nappes of the South-West Highlands, according to Prof. E. B. Bailey. (B.L. = Ben Lui Fold; C.C. = Carrick Castle Fold.) The heavy lines are thrust planes or slides.

They were, however, possibly produced before the Siluro-Devonian folding, as they are independent of the great masses of the Newer Granites (Siluro-Devonian in age). It must be noted that one should be able to trace individual beds of rock through the various zones of alteration (see map, *Fig.* 23).

d. Professor E. B. Bailey's interpretation of the structure of the South-West Highlands is so important that two of his maps have been here reproduced (*Figs.* 23a and 24b with diagrammatic section *Fig.* 23c). It will be seen also from *Fig.* 23d that Professor F. E. Suess of Vienna has offered an explanation of the phenomena observed by Bailey.

3. The Southern Uplands.

This range consists of highly folded Ordovician and Silurian rocks covered unconformably by Old Red Sandstone, hence the date of the folding is accurately known. It is largely on this evidence that the date of the formation of the great mountains of the Central and North-West Highlands is assumed. Just as it is

[1] G. Barrow, *Proc. Geol. Assoc.*, vol. xxiii. (1912). See also Prof. C. E. Tilley's criticisms (*op. cit.*).

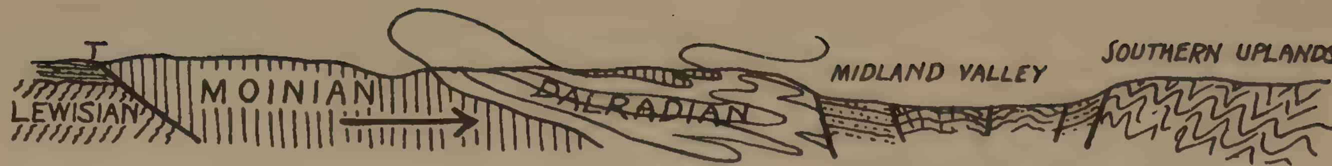

FIG. 23d. The Structure of the Scottish Highlands according to Professor F. E. Suess (*Geol. Mag.*, vol. lxviii., 1931, pp. 71-81). Compare this with *Fig.* 21.

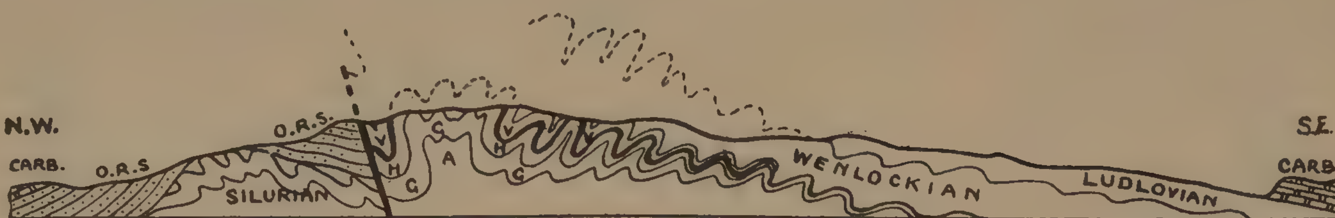

FIG. 24. Diagrammatic Section across the Southern Uplands of Scotland. A, Arenig. G, Glenkiln. H, Hartfell. V Valentian. Length of Section about 45 miles. (*L.D.S.*)

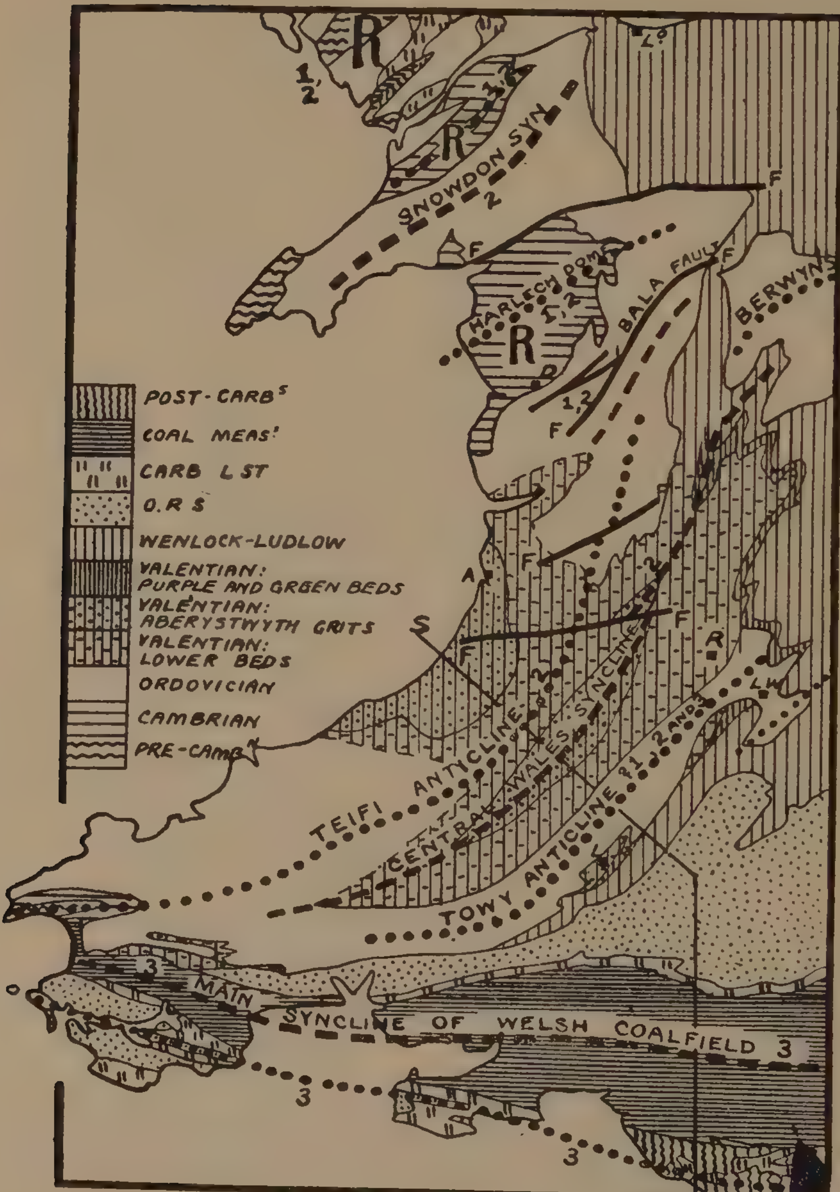

FIG. 25. Structural Map of Wales. R = Resistant Blocks. The numbers against the lines of folding refer to the date of their formation: 1 = Early Palæozoic (mainly Ordovician); 2 = Siluro

known that the movements continued intermittently through the Devonian Period, so they may have commenced earlier in the latter regions. But in the North-West Highlands Cambrian rocks are affected, and the movements are at earliest post-Cambrian. The structure of the Southern Uplands is that of an anticlinorium, in which the isoclinal folds on either side of the main axis dip in towards the centre (*i.e.*, fan-shaped in section), as shown in the diagram (*Fig.* 24). The boundary faults along the northern edge of the Southern Uplands and along the south-eastern margin of the Highlands (which are also the faults bounding the "Rift Valley," or Midland Valley of Scotland) are partly Siluro-Devonian, but renewed movement took place along them in Carbo-Permian times. The fold of the Southern Uplands continues across into Ireland.

4. Wales.

The general Caledonian trend of the Older Palæozoic rocks of Northern and Central Wales connects them with the south-eastern corner of Ireland, and hence the name "St. George's Land" (from St. George's Channel), which has been given to this tract. Whilst the main flexures, the cleavage and some of the faulting, especially in North-Western Wales, originated during the Siluro-Devonian period of earth-movement, it must always be remembered that the later Carbo-Permian folding followed the same lines. This is well shown in the structural map and section of Wales (*Figs.* 25-6), where the Towy Anticline has a typically Caledonian trend, but involves Old Red Sandstone. The structure of many parts of

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FIG. 25 (*continued*).

Devonian (Caledonian folding); 3 = Carbo-Permian (Armorican). The case of renewed movement should be noted, and also that the folds, on the whole, become newer south-eastward. In nearly all cases the "synclines" and "anticlines" would be better described as synclinoria and anticlinoria. Only a very few of the major faults are shown: there are many others of great importance, especially in North Wales. [For the sake of simplicity, the numerous large thrust faults in Anglesey have not been indicated, but their age is noted (1, 2).] The Silurian in the northern part of the map has not been divided. A few important towns are indicated: L = Llandovery; LW = Llandrindod Wells; R = Rhayader; A = Aberystwyth; D = Dolgelley; LO = Llandudno; S = Line of Section. (*L.D.S.*, adapted from *O. T. Jones* and others.) [Since this map was prepared several important papers dealing with the structure of North Wales have been published. The Bala Fault is in reality one of a series of thrust faults, many of which pass further east than shown, into the Llangollen district (age mainly 1, 2). There are also N.-S. faults (age 3) in the latter area. The Central Wales Syncline passes to the west, not to the east of the Berwyn Hills. The later work of Dr. W. H. Pugh added to the knowledge of the area north-east of Aberystwyth.]

North Wales is still imperfectly understood; thrust planes and overfolds on a scale comparable with those of the North-West Highlands have now been shown to exist in Anglesey superimposed on others of Pre-Cambrian age. It is claimed by some that important thrust planes of post-Silurian date occur on the mainland of Wales. It has also been stated that there is evidence of movement as outlined above (North-West Highlands, b.)—*i.e.*, underriding of great masses. Thrust planes certainly occur, but whether they should be regarded as of major importance is another matter. The Siluro-Devonian folding of North Wales may have been connected across the Irish Sea with that of the Lake District.

5. Lake District.

The study of the structure of the Lake District is one of absorbing interest, about which very diverse views have been held. The reader will find the views of Prof. Marr in his "Geology of the Lake District."[1] Perhaps more consistent with the general character of Siluro-Devonian folding is the interpretation given by Mr. J. F. N. Green.[2] The region was gently folded in Middle Ordovician times and Bala and Silurian rocks laid down unconformably on older strata. All the rocks were then intensely folded and cleaved by the Siluro-Devonian movements, and the general structure of the district is that of a great anticlinorium—parallel to and closely resembling that of the Southern Uplands—with a subsidiary synclinorium to the north. Against this ridge the Carboniferous rocks were laid down, and the features of the Lake District of the present day are largely due to the Carbo-Permian and Tertiary movements. (See map, *Fig.* 27.)

6. The South Wales—Belgium Ridge.

A comparatively low ridge must have bounded the Devonian Sea on the north, and separated it from the Old Red Sandstone lakes in that direction. Despite its probably insignificant elevation, this barrier becomes of increasing importance through the Devonian period and into the Lower Carboniferous (when it separates the Northern and South-Western Provinces of Carboniferous Limestone). In Northern France and Belgium its course from the Straits of Dover, through the Cambro-Silurian "Brabant Massif" (under Brussels), and further east-north-eastwards is quite clear. Its exact position under the Mesozoic cover of South-Eastern England is not so certain. Dr. J. W. Evans (*Proc. Geol. Assoc.*, vol. xxxiii., 1922) did not believe this ridge existed in the Bristol Channel region, and it is probable that the Old Red Sandstone of the Welsh border was deposited in a bay or gulf of the Devonian Sea. But one must remember that almost throughout South Wales the Old Red Sandstone type of Devonian rests unconformably on older rocks. Moreover, the lowest Devonian beds are there sometimes absent, whereas there is a complete and conformable succession from the Silurian to the Devonian in Shropshire.

[1] Cambridge, 1916.

[2] J. F. N. Green, "The Geological Structure of the Lake District," *Proc. Geol. Assoc.*, vol. xxxi. (1920), pp. 109-126. For later work see T. Eastwood, British Regional Geology, Northern England, 2nd Ed., 1946, and S. E. Hollingworth, *Proc. Geol. Assoc.*, vol. lxv. (1954), pp. 385-402.

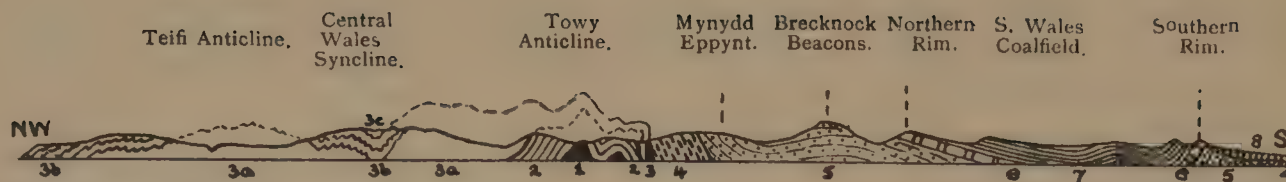

FIG. 26. Diagrammatic Section across Central and Southern Wales, showing principal axes of folding (partly after *O. T. Jones*). 1, Igneous Rocks of Llanwrtyd; 2, Bala; 3, Valentian (3a = Lower Beds, 3b = Aberystwyth Grits, 3c = Purple Shales at summit of Valentian); 4, Wenlock and Ludlow; 5, Old Red Sandstone; 6, Carboniferous Limestone; 7, Coal Measures; 8, Mesozoic. Scale about 10 miles = 1 inch.

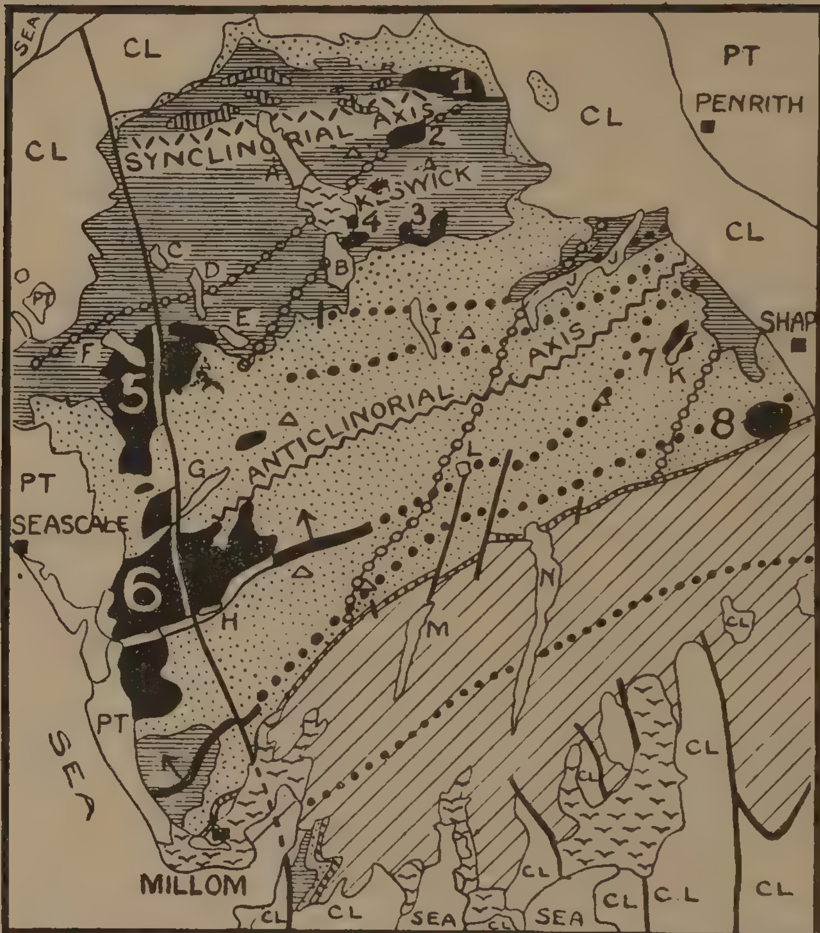

FIG. 27. Structural Map of the Lake District (after *J. F. N. Green*). Scale, 20 miles to one inch. Explanation: Horizontal lines = Skiddaw Slates; Dotted = Borrowdale Volcanic Series (Lower Ordovician); Vertical lines = Coniston Limestone (Bala); Oblique lines = Silurian; Solid Black = Igneous Intrusions; CL = Carboniferous Limestone; PT = Permo Trias; Heavy Black lines are faults; Chains of Circles = Ordovician (pre-Bala) Anticlines; Chains of Dots = Devonian Anticlines, some passing westwards into faults; Triangles = Chief Peaks. Lakes: A. Bassenthwaite; B, Derwent Water; C, Lowes Water; D, Crummock Water; E, Buttermere; F. Ennerdale Water; G, Wastwater; H, Devoke Water; I, Thirlmere; J, Ullswater; K, Hawes Water; L, Grasmere; M. Coniston Water; N, Windermere. *Intrusions*: 1 = Carrock Fell Com-

THE DEVONIAN VALLEYS AND BASINS OF DEPOSITION.

These are naturally found between the main mountain ranges.

1. **The Orcadie Basin,**[1] between the North-West Highlands and the Central Highlands.
2. **The Caledonia Basin,** between the Central Highlands and the Southern Uplands, stretching into Ireland and also round the eastern end of the Southern Uplands into the Cheviot Region.

FIG. 28. Diagrammatic Sections across the Lake District. From North to South. The upper figure shows the disposition of the rocks in early Silurian times and the effect of the pre-Bala folding; the lower figure shows the effects of the Siluro-Devonian Earth Movements. (*L.D.S.*, after *J. F. N. Green.*) (Compare also later work of G. H. Mitchell *vide supra* p. 77.)

FIG. 27 (*continued*).

plex (gabbro, etc.); 2=Skiddaw Granite; 3=St. John's Micro-granite; 4=Minor Intrusions; 5=Buttermere Granophyre; 6=Eskdale Granite; 7=Hawes Water Quartz-Dolerite; 8=Shap Granite; Nos. 1—7 are all probably associated with the Ordovician vulcanicity and are pre-Upper Bala in age; No. 8 is associated with the Siluro-Devonian Earth Movements.

[1] The non-committal term "basin" seems better than the too definite "Orcadie Lake," "Caledonia Lake," etc., since it is generally agreed that the Old Red Sandstone deposits were laid down by mountain torrents and streams and that any sheets of water were short lived or local.

3. **The Southern Irish Area.**
4. **The Welsh Gulf,** south-east of the Welsh Mountains.
5. **The Devonian Sea of Devon and Cornwall.** The deposits in each of these areas will be considered separately.

THE DEVONIAN OF THE BRITISH ISLES.

A. OLD RED SANDSTONE FACIES.

1. The Orcadie Basin.

The deposits of this basin may be considered as including those on either side of the Moray Firth, those in the Orkneys and Shetland Isles, and possibly also some occurring on the western coasts of Norway. It was evidently a deep mountain-girt basin, into which poured raging torrents from the surrounding mountains. Consequently it is largely filled up by an enormous thickness (probably over 20,000 feet in Caithness) of sediments ranging from coarse conglomerates and breccias, through coarse sandstones to flagstones, with shales and some lenticular limestones. The beds are classed as Middle and Upper Old Red Sandstone, and, especially in the Middle Old Red Sandstone of Caithness, a number of horizons have been distinguished by means of fish remains. The Middle Old Red Sandstone is characterized by certain plant types such as *Ptilophyton thompsoni* (stem = *Caulopteris peachi*). Among the fish *Thursius* and *Dipterus* characterize the lowest beds, followed by *Coccosteus*, and then a rich fauna appears in the "Achanarras Band," whilst an almost entirely different fish fauna appears in the highest beds. The Upper Old Red Sandstone is characterized by *Holoptychius* spp., *Psammosteus* spp., *Bothriolepis*, etc. There is a very considerable unconformity at the base of the Upper Old Red Sandstone. A few igneous rocks occur in the Middle Old Red Sandstone of the Shetland Isles, and in the Orkneys there is a feeble development of volcanic rocks in the Upper Old Red Sandstone.

2. The Caledonia Basin.

The principal area included in this basin of deposition is the great trough known as the Midland Valley of Scot-

land. The Old Red Sandstone crops out on either side of the Carboniferous Rocks, and is banked up against the Highland Rocks on the north and the Silurian Rocks on the south. The basin probably extended south-eastwards, as stated above, to include the Cheviot Region, whilst a bay seems to have stretched up to Oban on the West coast.

The deposits are divided into Lower and Upper Old Red Sandstone.

THE LOWER OLD RED SANDSTONE—up to 15,000 feet thick in Angus — consists of coarse conglomerates with huge rounded boulders, passing up into a succession of coarse sandstones with interbedded lavas at various horizons. The Lower Old Red is divisible into Downtonian below and Dittonian above (for definition see after, page 119). Like the Welsh Gulf, the Caledonia Basin may have originated as a cut off arm of the Ludlow Sea, and consequently the lowest beds include marine and brackish fossils such as *Platyschisma helicites, Lingula minima,* etc., associated with a series of finely preserved fish (especially in certain localities of the Southern Uplands), including *Thelodus, Lanarkia* and *Birkenia.*[1] The Downtonian rests unconformably on the older Palæozoic rocks of the Southern Uplands, though sometimes the discordance in dip is but poorly marked; to the north of the Caledonia Basin there is a great unconformity, and the beds rest on Cambrian (?) and Highland Rocks. The overlying Dittonian often has conglomerates at the base. It is characterized by *Cephalaspis lyelli, Pterygotus, Eurypterus,* etc.

The numerous volcanic rocks of the Lower Old Red Sandstone have already been described.

THE UPPER OLD RED SANDSTONE of the Midland Valley rests with a very marked unconformity on the folded and denuded lower division. Moreover, its basal conglomerates include fragments of the Lower Old Red Sandstone lavas, and even of the granites. The beds comprise conglomerates and red sandstones, and pass up

[1] It should be noted that many of these fish are recorded as "Silurian," but there is every reason to consider the beds in which they occur as equivalent to the Downtonian of the Welsh Borderland.

gradually into the overlying Carboniferous. Partly for that reason and partly from the characters of the flora, the Upper Old Red Sandstone is sometimes considered as the base of the Carboniferous. Fossils include the fish *Holoptychius* and *Bothriolepis*.

In the North of Ireland (the westward extension of the Caledonia Basin) there is no apparent break between the Upper and Lower Old Red Sandstone, otherwise the beds are quite comparable with those in the Midland Valley except for the feeble development of igneous rocks.

3. Southern Ireland.

Details of this basin of deposition are still very obscure. The Dingle Beds succeed the Ludlow Beds conformably, and are regarded by some as Silurian. They are a thick series of unfossiliferous sandstones. The overlying beds, which may be regarded as true Old Red Sandstone, rest on them with marked unconformity. The basal conglomerates of the latter series pass up into Yellow Sandstones (Kiltorcan Beds), which have a freshwater and terrestrial fauna of fairly late Devonian age (including the plants *Archæopteris*, *Bothrodendron*; the mollusc *Archanodon jukesi*, together with a few fish fragments such as of *Coccosteus*). The succeeding Coomhola Grits have marine bands like those occurring at the top of the Old Red Sandstone in Pembrokeshire.

4. The Welsh Gulf.

The deposits in this area differ in many respects from those in the areas previously described. The Welsh Mountains were lower, so that the great torrential conglomerates of the Scotch basins give place to finer grained sediments. More important than that, the proximity of the Southern Sea (of Devon and Cornwall) is apparent, not only in the lower beds but again in the highest part. So much is this so that the lower series of deposits may be regarded as transitional between those of the marine Silurian below and those of the more clearly lacustrine Upper Old Red Sandstone above. In view of the different meanings which have been attached to the term "Lower Old Red Sandstone," it is better that the name should

be dropped in connexion with the Welsh area. The succession is as follows:

b. UPPER SERIES (Old Red Sandstone Facies).
a. LOWER SERIES (Old Red Sandstone Facies). { 2. DITTONIAN. 1. DOWNTONIAN.

DOWNTONIAN.

It is possible to picture the conditions at the commencement of the Devonian. An arm of the Upper Silurian Sea was almost cut off, probably by the uprise of the ridge from South Wales to Belgium, and a basin of comparatively limited extent was left. By the influx of freshwater or from further folding, the waters of this area commenced to transgress in several directions, including southwards and south-westwards against the submerged ridge. Conditions gradually became less and less suitable for the existence of marine creatures, and more and more truly lacustrine. The change is reflected in the fauna of the lower part of the Downtonian. It falls into three groups:

a. Upper Ludlovian marine species which survived the initial change of conditions, and struggled to live on. They often became stunted, and gradually died out as conditions continued to grow less marine.[1] Examples are *Chonetes striatella*, *Retzia bouchardi* and *Orthis* spp.

b. Species of brackish or shallow-water marine creatures which flourished for a short time during the change of conditions. These include many forms restricted to the lower Downtonian — *Platyschisma helicites, Holopella, Beyrichia*, *Lingula minima*, *L. cornea*, Eurypterids, etc. These also died out as conditions became more lacustrine.

c. The forerunners of the succeeding Devonian (Old Red Sandstone) faunas. There were probably living in the Upper Ludlovian sea the ancestors of the great group of the Fishes—leathery skinned creatures with no hard parts which could be preserved as fossils. Evolution is often hastened by unfavourable conditions, and whether

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[1] Until recently all these beds with marine fossils were regarded as Silurian, for that reason the Temeside Shales were made the highest beds of that system. This classification is adhered to by a number of geologists, but there seems to be an increasing tendency to use the grouping here given in detail. See L. D. Stamp, *Geol. Mag.*, vol. lx., 1923, especially pp. 276-282, p. 410 and vol. lxi., 1924, pp. 351-355. The grouping here adopted has been agreed by T. Robertson, of the Geological Survey (*Geol. Mag.*, vol. lxv., 1928, p. 395), and more recently by a group working in the area.

it was that or not, in this case the fishes commenced to develop hard parts. At first they developed bony stud-like processes (dermal tubercles) as in *Thelodus*, or little spines, as in *Lanarkia*, scattered over the surface of the leathery skin. At a later stage in the evolution the studs coalesced to form bony plates, and then the originally separate studs became reduced to form ridges (as in *Tolypaspis*), or even fine striate ornamentation on thick plates of bone (*Cyathaspis* and *Pteraspis*). Almost without exception remains of fish occur for the first time in the lowest Downtonian, and hence the dawn of the Devonian corresponds with the dawn of an age of Fishes Whilst the ancestors of the fish were probably marine, they rapidly became adapted to lacustrine conditions, and are the dominant fossils of the Downtonian and succeeding beds of Old Red Sandstone type. Only a few appear to have become adapted to life in the sea, though some could live in either fresh or salt water (*Pteraspis*).

The Downtonian is identified by its fish-fauna, there being a large number of forms which, first appearing at this horizon, do not survive into the Dittonian. These include *Thelodus, Birkenia, Onchus, Cyathaspis, Tolypaspis* and *Cephalaspis murchisoni.*

The beds forming the Downtonian in the Welsh Gulf are—

3. Red Marls—up to 1,800 or more feet in thickness—with nodules and bands of cornstones.[1] Two important fish-bearing horizons occur :—
   Trimpley Fish Beds.
   Ledbury Fish Beds.
2. Temeside Shales—greenish nodular shales (not always present). } up to 500 feet.
1. Downton Castle Sandstone and "Tilestones" (thinly bedded micaceous sandstones suitable for use as roofing tiles) with the Ludlow Bone Bed at the base. } up to 500 feet.

The **Ludlow Bone Bed** is a band from a fraction of an inch to a foot or more in thickness, consisting of rolled fragments of the earliest fishes—especially *Thelodus*. They must have literally swarmed in the water, and so have been killed off in vast numbers by some earthquake shock or change of conditions. The bed is remarkably constant; resting conformably on the Upper Silurian in the centre of the basin it passes laterally into a conglomeratic Bone Bed, and then into a sandstone, resting with marked unconformity on underlying beds.

[1] Concretionary inorganic calcium carbonate. Found in many deposits being formed under desert or semi-desert conditions at the present day.

The **Downton Castle Sandstone** also contains numerous fish remains, together with surviving marine creatures; sometimes it is thinly bedded and very micaceous (tilestones).

The **Platyschisma Shales** are lateral equivalents of the lower part of the sandstone, and are found towards the centre of the basin, where marine conditions persisted longer.

The **Temeside Shales.** By this time most of the marine creatures had died out.

The **Red Marls** (Red Downtonian). The marine *Lingula* persisted until after the Ledbury Fish Beds had been deposited. The monotonous red marls with their calcareous concretions or more continuous cornstones may be paralleled at the present day in certain shallow depressions in arid areas.

DITTONIAN.[1]

This division also comprises a thick series of red marls with sandstones and cornstones, but differs from the Downtonian in the presence of the fish *Pteraspis* (completely absent in the latter)—especially *P. rostratus* and *P. crouchii* — and *Cephalaspis lyelli.* Succeeding the marls and into which they gradually pass is a series of sandstones with marl bands—the Senni Beds. They are well developed round the northern rim of the South Wales Coalfield, and give rise to great stretches of barren mountainous country (Brecknock Beacons, etc.).

UPPER SERIES (so-called Upper Old Red Sandstone).

There is no apparent discordance in stratification between the Upper Series and the Dittonian, but probably a great break in time. The former overlaps and rests on Silurian Rocks in the Gower Peninsula, Tortworth Inlier (north of Bristol) and the Mendip Hills. The lower beds are the " Brownstones,"—brown, red or green sandstones with red marls—containing plant remains of Upper Old Red Sandstone type. They pass up into the conglomerates above. The pebbles in the latter are mostly of quartzite and jasper, the latter believed to have resulted from the " jasperization " of various rocks under desert conditions. The associated sandstones yield *Holopty-*

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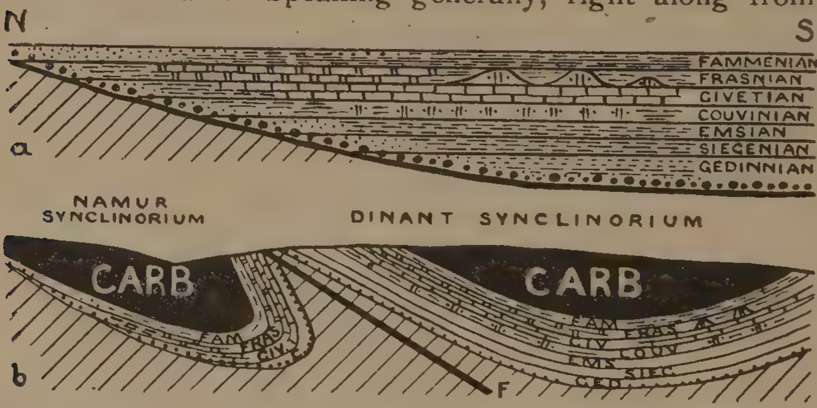
[1] The Downtonian, in the sense in which that term is here used, has only recently been defined on a palæontological basis and its upper limit fixed. It then became necessary to assign some name to the remainder of the " Lower Old Red Sandstone," and Mr. W. W. King introduced the term " Dittonian." Mr. King has summarized his work on the whole succession (*Proc. Geol. Assoc.*, vol. xxxvi., 1925, pp. 383-389).

chius, *Bothriolepis* and other Upper Old Red Sandstone fish. An interesting fossil of the Upper Series in South Wales is the supposed freshwater mussel, *Archanodon jukesi*. In Pembrokeshire there occur intercalated in the Upper Series certain beds with marine fossils, and it appears that towards the close of the Devonian period the sea of Devon and Cornwall transgressed so far to the north as to override the ridge and to invade this corner of the Welsh Gulf.[1] The Upper Series of the Old Red Sandstone passes up gradually and conformably into the shales at the base of the Carboniferous.

B. THE MARINE (DEVONIAN) FACIES.

Devon and Cornwall, etc.

With the uplift of the London-Belgium Ridge the sea, at the commencement of Devonian times, was pushed to the south. The history of the Devonian period is largely that of the invasion of this ridge by the sea from the south. Speaking generally, right along from



FIGS. 29 and 30. Diagrams illustrating the Devonian Transgression in Belgium. a = The successive overlap of the Devonian Beds, due to marine transgression from the south. Notice the coastal deposits (indicated by dots) and the principal limestones and coral reefs (deeper water). b = The beds folded and denuded, as seen at the present day (minor folds omitted). Carb. = Carboniferous Beds. (*L.D.S.*)

[1] The beds of Old Red Sandstone type, which occur intercalated with marine beds in North Devon, may indicate that the waters of the Welsh Gulf frequently overflowed and poured sediment southwards.

Cornwall to Belgium there was a great marine transgression, interrupted at intervals by temporary retreats of the sea, leaving areas of shallow water in which deposits almost of Old Red Sandstone type were laid down. Roughly, however, each successive division of the Devonian overlaps the preceding towards the north. The movement was continued in Carboniferous times, and hence is known as the Devono-Carboniferous transgression. The beds so laid down were intensely folded at the end of the Carboniferous Period. These Carbo-Permian folding movements have so intensely affected the Devonian of Cornwall and Devon that the beds are much altered and repeated by reversed faults, making even the main succession difficult to determine. For this reason it is of great advantage to study the succession further east along the strike—that is to say, in Belgium.[1] There the beds, laid down as in the first figure (*Fig.* 29) facing, have been folded into two great synclinoria. The southern synclinorium (of Dinant) has been thrust northwards by the Carbo-Permian movements over the northern one (of Namur) as shown in the second figure (*Fig.* 30).

The typical succession in Belgium is as follows, though naturally the beds undergo great lateral variation, and there are littoral representatives of each division.

U.D.
- Famennian—shallow-water beds with Upper Old Red Sandstone plants (*Archæopteris hibernica*) and fishes (*Bothriolepis*) as well as a marine fauna.
- Frasnian—shales with beds of limestone and numerous coral reefs. *Spirifer verneuili.*

M.D.
- Givetian — massive dark limestone. *Stringocephalus burtini.*
- Couvinian—calcareous shales. *Calceola sandalina.* Below are sandy beds with *Spirifer cultrijugatus.*

L.D.
- Emsian[2]—shales and sandstones. *Spirifer arduennensis.*
- Siegenian[2]—sandstones and shales. *Spirifer excavatus, S. primævus.*
- Gedinnian
  - Upper—shallow-water beds with *Pteraspis* (=Dittonian).
  - Lower—marine beds (=Downtonian).

The letters L.D., M.D. and U.D. stand for Lower, Middle and Upper Devonian respectively.

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[1] L. D. Stamp, "The Geology of Belgium," *Proc. Geol. Assoc.*, vol. xxxii. (1922), pp. 4-6; E. Maillieux, *Ibid.*, pp. 11-19.

[2] Formerly grouped together as Coblentzian.

	Cornwall and South Devon	North Devon and West Somerset
Famennian	Green and Purple Slates, etc.	Lower Pilton Beds Baggy and Marwood Beds (marine) Pickwell Down Sandstone (with Upper O.R.S. fish, *Holoptychius* and *Bothriolepis*)
Frasnian	Calcareous Slates, Limestones of Torquay, Plymouth, etc.	Morte Slates Ilfracombe Beds { Upper part with *Spirifer verneuili* Lower part ? age
Givetian	Hope's Nose Limestone	Combe Martin Beds Hangman Grits { Upper part (marine) with *Stringocephalus* Middle part with M.D. plant *Ptilophyton* Lower part ? fluviatile
Couvinian	Limestones with *Calceola*.	
Emsian	Staddon Grits { Beds with *Sp. cultrijugatus* Beds with *Sp. arduennensis* Beds with *Sp. hercyniæ*	?
Siegenian	Meadfoot Beds with fossiliferous Looe Beds	Lynton Beds with *Pteraspis* Foreland Sandstone
Gedinnian { Upper Lower	Dartmouth Slates ?	— —

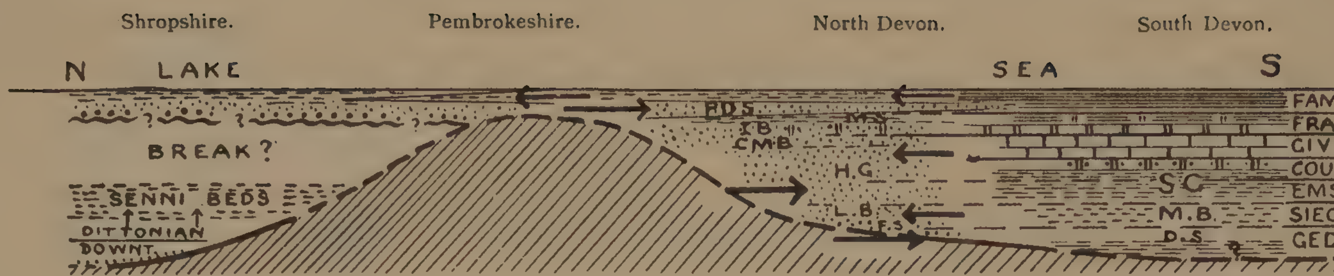

FIG. 31. Diagrammatic Section through the deposits of the Welsh Gulf and the Devonian Sea of North and South Devon. The beds may be identified from the table opposite. Arrows from the north indicate Continental influences (presence of beds of "Old Red Sandstone" type, etc.); arrows from the south, marine influences or invasions. All these beds, especially to the south of the barrier, were intensely folded during the Carbo-Permian movements. (*L.D.S.*)
Recent work seems to show that the importance of the ridge is here considerably exaggerated.

The Devonian in Belgium has been carefully studied, is well exposed and very fossiliferous. It therefore serves as a type with which the Devonian of Devon and Cornwall may be compared.

Passing westwards from Belgium, the inlier of the Boulonnais (between Calais and Boulogne), is a continuation of the northern border of the Namur Synclinorium. The lowest Devonian beds are Givetian in age, and rest unconformably on Silurian.

Under London, Frasnian Beds, with a characteristic marine fauna, are known, and also beds of Famennian age, both of marine (at Cheshunt) and of Old Red Sandstone types (at Southall, with *Holoptychius*, etc.).

It is quite probable that the west of England Devonian area is a direct continuation of the Namur Synclinorium. Until recently it was thought that the Devonian was practically complete in both North and South Devon, but Dr. J. W. Evans discovered *Coccosteus* (a Middle Devonian fish) and *Stringocephalus* (Givetian) in the Hangman Grits of North Devon. This places these Grits much higher in the sequence, and it is now very probable that the lowest Devonian is unrepresented in North Devon. Unfortunately, the base of the system is not visible in either North or — at least clearly — in South Devon, but there is now some evidence of a northward transgression of the sea in Devonshire, just as one has in Belgium. An attempt has been made to show this in the annexed diagrammatic section from South to North Devon (*Fig.* 31). The figure is based on the latest evidence available, but must not be taken as final. It shows roughly also the more littoral character assumed by the various beds when traced northwards. For convenience in reference the correlation is also tabulated.[1]

Looking at the general aspect of the beds it should be noted that

(1) In the south they are of a predominantly deeper water type than in the north. Some of the limestones in the south may be coral reefs.

(2) In the north, as in Belgium, the beds become

[1] Compiled from J. W. Evans, *Geol. Mag.* (1919), pp. 547-9. *Proc. Geol. Assoc.*, vol. xxxiii. (1922), pp. 201-8, and E. Asselberghs, *Geol. Mag.* (1921), pp. 165-9.

more arenaceous and of shallower water type. It has already been mentioned that, in Belgium at least, the marine transgression from south to north was not continuous, but that there were local retrograde movements. The same seems to have happened in North Devon. There are three horizons in particular where the beds are of "Old Red Sandstone" type. It may be that at these periods the Welsh Gulf extended its southern boundary and poured down both sediment and fish into the Devonian Sea. These periods are:

a. Lower Devonian (Foreland Beds with *Psilophyton*).
b. Middle Devonian (Couvinian—lower and middle parts of Hangman Grits).
c. Upper Devonian (Lower Famennian — Pickwell Down Sandstone with *Holoptychius*).

Thus there is sometimes said to be an alternation of marine and "Old Red" conditions in North Devon.

(3) The greatest extent of the Devonian transgression was in Upper Famennian times. The marine bands of Pembrokeshire are of this age.

Details of the Beds—South Devon and Cornwall.

The Dartmouth Slates yield *Bellerophon trilobatus* and ill-preserved fish fragments of Lower Old Red Sandstone types.

The Meadfoot Beds are largely unfossiliferous sandstone, but about the middle of the series some siliceo-calcareous bands yield a typical Siegenian fauna, including *Orthis personata*, *Rhynchonella daleidensis*, *Spirifer hystericus*, *Pleurodictyum problematicum*. etc.

The Staddon Grits are not very fossiliferous, but appear to correspond to the Emsian and lower part of the Couvinian.

Shales and Limestones, with *Calceola sandalina* and other characteristic Couvinian fossils, pass up into the succeeding beds

Hope's Nose Limestone has Givetian fossils—*Cyathophyllum*, *Atrypa aspera*, etc.

The Massive and Shelly Limestones of Torquay, Plymouth, etc., are often crowded with fossils, mostly of Frasnian age (though some are of Givetian age), including *Spirifer verneuili*, *Rhynchonella cuboides* and numerous corals (*Phillipsastræa*, *Heliolites porosa*, *Cystiphyllum*, etc.).

The Higher Beds of the Devonian are mainly mudstones, with lenticular limestones, followed by red and green slates, with *Entomis serratostriata*, etc.

Above the Staddon Grits the succession in Cornwall cannot be exactly correlated with that of South Devon, as detailed above. The beds are less calcareous, and apparently of deeper water origin (slates). The occurrence of pillow-lavas is of interest.

North Devon and West Somerset.

The Foreland Sandstones are, as a rule, unfossiliferous. They have yielded the plant *Psilophyton.*

The Lynton Beds are occasionally fossiliferous, and seem to be Siegenian in age.

The Hangman Grits again have few fossils, but the succeeding beds:—

The Combe Martin Beds yield *Stringocephalus burtini* (Givetian).

The Ilfracombe Beds have yielded *Spirifer verneuili* and *Rhynchonella cuboides* at quite a low horizon, and must therefore be Frasnian in the main.

The Morte Slates have aroused considerable interest, in that their rare fossils were said to indicate a Lower Devonian or Silurian age, and the beds were regarded as a faulted inlier. But the fossils were badly preserved, and the typical Upper Devonian *Sp. verneuili* has now been found.

Of the Famennian the lower parts are represented by the Pickwell Down and Baggy and Marwood Beds.

The Pilton Beds, Devonian in the lower part, appear to grade up gradually into beds of Carboniferous age.

THE DEVONIAN IGNEOUS ACTIVITY.

The igneous activity did not quite follow the usual order as an intrusive phase seems to have preceded the main phase of extrusion :—

1. Intrusion of great masses of granitic composition coincident with the main period of folding. ("Newer Granites" of Scotland.)
2. Extrusion during Lower Old Red Sandstone times—commencing as early as the Downtonian.
3. Intrusion of granite masses which penetrate the lavas—also completed before the close of the Lower Devonian.
4. Phase of minor intrusions and slight renewed extrusion.

Except for slight extrusion in the Upper Old Red Sandstone the whole seems to have been completed before Upper Devonian times, and fragments both of the volcanic and plutonic rocks abound in Upper Old Red Conglomerates.

A. Extrusive Rocks.

Two widely different areas may be distinguished :—

1. Devon and Cornwall, associated with the slowly sinking sea-bottom and the Devonian transgression, and hence of the Spilitic Suite. Spilites occur in the Middle and Upper Devonian of South Devon and Cornwall, and are associated with albitized dolerites recalling the Welsh Ordovician types.

2. Scotland, closely associated with the great folding movements, and hence belonging to the Pacific Suite.

The Volcanic Rocks are situated in three main areas along three of the valleys shown on the map (*Fig.* 18).

a. Lorne and Glencoe Districts.

b. Extensive tracts on either side of the Midland Valley, including the Ochil and Sidlaw Hills, and part of Arran on the north and the Pentland Hills on the south.

c. The Cheviot Hills and the Scottish Borderland.

In all these areas lavas are predominant, and from the small proportion of tuffs and breccias it is evident that the igneous action was not of the explosive type. In some districts the old vents or necks can be traced. In the Lorne district[1] the lavas rest directly on old crystalline schists, but elsewhere they are interbedded with the sediments, and may commence as early as the Downtonian (Highland Border). They may attain a great thickness (6,500 feet in the Ochil Hills). The lavas are mostly basic pyroxene andesites grading into olivine basalts, together with some dacites or rhyolites, and some enstatite-bearing rocks.

B. Intrusive Rocks.

1. EARLIER SERIES ("NEWER GRANITES" of Scotland).

Through the greater part of the Highlands of Scotland, as well as the Southern Uplands and the adjoining Lake District, there is a great series of intrusive masses, mostly of large size. Many are boss-like masses, others have a stratiform habit. The masses near Aberdeen (Aberdeen Grey Granite) are particularly famous. They are mainly biotite or hornblende granites and quartz-diorites, non-porphyritic and medium grained. Several fine examples of plutonic complexes occur, with gabbros, norites and ultrabasic rocks, but acid rocks are predominant. Themselves little altered, the granites are slightly younger than the main folding, and penetrate highly altered and folded rocks; but pebbles of them occur in Lower Old Red Sandstone Conglomerates. The distribution of the masses is shown on the map (*Fig.* 32). Some of the Irish Granites (Leinster) are of the same age.

2. LATER SERIES (later than the Lower Old Red lavas).

Occur in two principal areas associated with lavas:—

a. Caledonian Valley-line of Glen More (Beinn Cruachan and Beinn Nevis masses).

b. Cheviot Hills.

Some Lake District intrusions may be of this age (Skiddaw and Shap Granites and the Eskdale-Wastdale mass).

The Beinn Cruachan and Beinn Nevis masses are great plugs with vertical walls, and have been intruded in two parts, the inner being more acid. The dominant rocks are hornblende granites and quartz diorites, but belong really to the Monzonite Family (Adamellites) having orthoclase and plagioclase felspars in equal proportions.

C. Minor Intrusions.

The representatives of this phase are mostly dykes and small sills. In the Lorne and Beinn Nevis districts the dykes have a

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[1] In the Glencoe district is found the famous example of "Cauldron Subsidence." A group of Lower Old Red Sandstone lavas have been let down by curved faults into the midst of crystalline schists. A similar plug forms the summit of Ben Nevis.

FIG. 32. Map of Scotland showing the distribution of Devonian Igneous Rocks (after *Harker*). Plutonic Rocks shown in solid black, Volcanic Rocks by vertical lines. The localization of the latter along three of the valleys or basins produced by the Siluro-Devonian folding should be noted. This may be due to denudation over intervening areas. Some of the more interesting localities are indicated: *Older Intrusions:* Cairngorm, very large mass, Aberdeen (A), Peterhead (P), Huntly and Ellon (H and E, plutonic complexes with basic and ultrabasic rocks), Garabal Hill (G.H.—interesting complex) and the Galloway Granites (G including also the Dalbeattie mass, D).

N.E.-S.W. direction, and tend to be crowded together on the north-eastern and south-western sides of the Granite masses. Some of them are older than the *central* parts of the great granitic intrusions. Round the Lake District bosses the dykes have a radial arrangement. Dykes also occur in the Cheviot Hills. The rock types present include (a) hornblende- and mica-porphyrites, (b) quartz-porphyries and (c) mica- or hornblende-lamprophyres, and they generally follow one another in this order.

The later extrusive episodes are restricted to one or two small areas—in the Middle Old Red Sandstone in the Shetlands, in the Upper Old Red Sandstone in one of the Orkney Isles and in Arran.

ECONOMIC GEOLOGY OF THE DEVONIAN.

1. Building Stones. Sedimentary Rocks. Some of the Old Red Sandstones of Scotland furnish good building stones, and are much used locally. In Devonshire, especially in the neighbourhood of Torquay, the limestones were quarried for interior and ornamental work as well as for building.

Igneous Rocks. Of enormously greater importance is the granite industry of Scotland and Ireland. The best known types are the grey granites of Aberdeen and the pink of Peterhead. Here granite quarries are favourably situated for sea-transport. Equally well known is the Shap Granite of Westmorland—contrasting greatly with the uniform textured grey rock of Aberdeen. It is pale pink or reddish, with large porphyritic crystals, and, much used as an ornamental stone all over these islands, it is easily recognized. The Irish granites (especially in County Wicklow) give rise to an important industry

2. Road Metal. The waste from the granite quarries is largely used, and many other stones are in local use. Amongst the latter may be noted the cornstones of the Welsh borderland, which, occurring as they do in a country of soft red marls were once in considerable demand.

3. Roofing Slates. Slate-quarrying is an important industry in Devon and Cornwall. The well-known Delabole Quarries are in Upper Devonian Slate.

4. Scenery and Agriculture. These vary greatly according to the local character of the rocks. In South Devon wide expanses of heather-covered moorland occur, but the scenery is largely controlled by the intrusive Carbo-Permian granites. In North Devon the tract of Exmoor is typical. In the Welsh Borderland the Downtonian and Dittonian marls afford some of the most fertile soil in the West Country — as evidenced by the Cider Apple Orchards of Herefordshire—yet a short distance away the same

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FIG. 32 (*continued*).

Lavas: Glencoe, Lorne (L), Stonehaven (S, Downtonian lavas), Ochil Hills (O), Sidlaw Hills (Si), Pentland Hills (P) and Cheviots. *Newer Intrusions:* Beinn Cruachan, Beinn Nevis and Ballachulish (B, with basic rocks of the monzonite family —Kentallenite).

beds with the overlying sandstones give rise to some of the most desolate tracts of uninhabited, boggy moorland one could find (Mynydd Eppynt, Brecon), as well as to high mountains (Brecknock Beacons). In Scotland the same is true—the fertile valley of Strathmore and the wild lands of Caithness are both on Old Red Sandstone. In Ireland the tracts of Old Red Sandstone are mostly infertile.

5. Water Supply. The Devonian and Old Red Sandstone are of far less importance than the Ordovician and Silurian in this respect.

LIFE OF THE PERIOD.

In many ways the Devonian fauna is intermediate between that of the Silurian and that of the Carboniferous. Graptolites have disappeared, but most of the other groups abundant in Lower Palæozoic times persist, though in reduced numbers. The dawn of a new era is marked, however, by the appearance and abundance of Fishes—the earliest vertebrates—the virtual first appearance of land plants, the appearance and abundance of ammonoids with simple suture lines (Goniatites), the appearance of loop-bearing Brachiopods (Terebratuloids) and the common presence of Echinoids and Blastoids.

a. Plants. Plant-remains are abundant even in the lowest beds (*Psilophyton* and *Pachytheca* occur associated with the Ludlow-Bone Bed), and are, naturally, found more commonly in the Old Red Sandstone Facies. In the lower beds simple, dichotomously branched forms, which probably grew as masses in swampy places, occur. The remains are known loosely as "*Psilophyton*," but petrified specimens, now known from Aberdeenshire, have been named *Rhynia*. Rather more complex in its structure is *Asteroxylon*. In higher beds occur more highly developed plants, such as *Ptilophyton* (Middle Old Red Sandstone) and the forerunners of the Carboniferous Pteridosperms characterize the Upper Devonian—*Lepidodendron*, *Bothrodendron*. Some of the beds yielding these plants, however, may really be Carboniferous. *Archæopteris* and *Palæopteris* are more typical of undoubted Upper Devonian.

b. Vertebrata. Fish remains are found in both facies of the Devonian, but more abundantly in the Old Red Sandstone type. In the most primitive group—the Ostracoderms—the outer layer or skin is ossified; in later forms an internal skeleton and external scales are developed. *Cephalaspis*, *Cyathaspis* and *Pteraspis* are Ostracoderms from the lower division; the more advanced types (Dipnoids, etc.) in the middle division include *Coccosteus* and *Homosteus;* in the upper division *Holoptychius*, *Bothriolepis* and *Asterolepis*.

c. Arthropoda. Most of the Silurian genera of Trilobites remain, but in diminished numbers, and showing various signs of decadence. *Goldius* [*Bronteus*], with its large pygidium, is especially typical, *Harpes* combines a large head shield with a small degenerate pygidium, *Homalonotus* and *Phacops* are impor-

tant Eurypterids of enormous size are found in the Old Red Sandstone.

d. Mollusca. Lamellibranchs and Gastropods are increasingly important; amongst Cephalopods the Nautiloids with *Orthoceras*, *Cyrtoceras*, etc., remain important, whilst the Ammonoids, with simple suture lines (Goniatites), have been used as zonal fossils, and are very important.

e. Brachiopoda. Horny Inarticulata have become rare; spire-bearers (*Spirifer*, *Athyris*, etc.) are abundant: terebratuloids, with a short brachial loop (*Stringocephalus* and *Dielasma*) occur.

f. Echinodermata. Cystids have become practically extinct, Blastoids (*Nucleocrinus* and *Pentremites*) become important. Crinoids are very important (*Melocrinus*, *Cupressocrinus*, etc.).

g. Cœlenterata. Rugose corals (*Cyathophyllum*, *Acervularia* and *Phillipsastræa* as rock formers, also *Calceola*) and Tabulate corals (*Heliolites*, *Pachypora* and *Alveolites*) and Stromatoporoids are all very important in Devonian Limestones.

h. Protozoa—not important.

CHAPTER IX.

THE CARBONIFEROUS SYSTEM.

NAME. So called from its inclusion of the principal coal-bearing beds. The Carboniferous rocks are the most important of all the British strata. Not only do they occupy a great surface area, but they yield a great variety of substances of economic importance, including practically all the British coal.

INTRODUCTORY.

In most respects different parts of the Carboniferous period offer great contrasts. From a geographical point of view the whole Period falls into three :—

First the **Carboniferous Limestone Period.**
Secondly the **Millstone Grit Period.**
Thirdly the **Coal Measure Period.**

1. Carboniferous Limestone Period (Lower Carboniferous).

The great mountain ranges which arose in early Devonian times had, except in Scotland, been worn down to mere stumps when the sea invaded the Old Red Sandstone basins in early Carboniferous times. Thus, whilst the old Devonian barriers can be traced, separating arms of the Carboniferous sea, they yielded little detrital material, and in the clear though shallow waters great thicknesses of limestones were laid down. The chief exception to this statement is to be found in Scotland. In the Midland Valley of Scotland one is very close to the great land mass of the Highlands, and sandy material derived from the great mountains there still predominates. The deposition of sand and shales was interrupted at intervals by the growth of swampy forests along the coasts (giving coal seams), and occasionally also by widespread but short-lived invasions of the sea (giving thin marine limestones).

2. Millstone Grit Period.

Then came a time when a great river, sweeping down from the north-east from the land mass of Scotland and Scandinavia, overwhelmed the British area with great quantities of arenaceous debris. Needless to say, it did not spread itself over the whole area at once, and the deltaic conditions of the Millstone Grit came on at different times in different parts of the country. It may be that small earth-movements, heralding the catastrophic events of the end of the Carboniferous period, contributed to the change since, even away from the delta of this great river (as in South Wales) sandy rocks follow the Carboniferous Limestone.

3. Coal Measure Period.

The deltaic flats of the Millstone Grit period prepared the way for the growth of huge areas of swampy forest whose remains have been preserved as beds of coal. At intervals these forests were overwhelmed by masses of river-borne sediments, at other times the sea broke through and has left traces as thin marine bands. The period was brought to a close by a gradual desiccation spreading from north to south, and by a great series of earth-movements (described in the next chapter).

Despite the inequality of the three periods and the fact that they are not accurate time-divisions—that is, the Millstone Grit, for example, of the south of England was being laid down whilst Carboniferous Limestone was still in process of formation in the north—the Carboniferous System is most conveniently considered under these three divisions.

CARBONIFEROUS LIMESTONE PERIOD.
GEOGRAPHY OF THE PERIOD.

The broad outstanding features of the time were :—

1. The great land mass to the north, whose shore must have run approximately along the line of the Highland border and across to Ireland. Associated with this shoreline we not only have great coastal flats but also the manifestation of extensive volcanic activity—the pour-

ing out of sheets of basaltic lava and the intrusion of small masses as sills, dykes, etc. The igneous rocks belong to the Atlantic Suite of rocks — a suite which is associated with faulted coastlines.

2. The land mass of "Wales" or "St. George's Land," extending from South-eastern Ireland through the central part of Wales, to the Midlands of England. This land formed an important barrier between two main areas of deposition, a "South-western Province" and a "Northern Province." The sea encroached on this area from the north but retreated from it southwards in the South-western Province. The ridge was never entirely covered by sea in Carboniferous Limestone times, but there was probably free communication between the two areas of deposition round the western end of St. George's Land. It should be noticed that this barrier is further north than in Devonian times.

3. A low, narrow ridge with a Caledonian trend ran across the Lake District and may have formed part of a land mass connecting the Lake District, the Isle of Man and Northern Ireland. The Carboniferous Limestone beds of the southern side of the Lake District are clearly banked up against this old ridge.

CARBONIFEROUS LIMESTONE IN THE BRITISH ISLES.

The Carboniferous Limestone or "Avonian" has been carefully studied in several parts of Great Britain and has been divided into a number of zones, chiefly by means of corals and brachiopods. The zones are usually referred to by their index-letters (see below). Roughly, the lower three zones constitute the Tournaisian or Lower Carboniferous Limestone, the upper zones the Visean or Upper Carboniferous Limestone. A useful distinction between the two is the presence in the upper group of the coral *Lithostrotion*—a simple or compound coral easily recognized by its laterally flattened rod-like true columella.

Both the divisions Tournaisian and Visean (from Tournai and Visé) are founded on the Belgian development of Carboniferous Limestone ("Dinantian"), and when the succession was carefully compared with that in England it was found that the dividing line between the Tournaisian and Visean did not quite coincide

FIG. 33. Map showing the Movement of Avonian Shorelines in England and Wales (adapted from *Vaughan*). The approxi-

with that between the upper and lower groups in England. Hence there has been some confusion as to the exact meaning of "Tournaisian" and "Visean."[1] For that reason "Upper Avonian" and "Lower Avonian" are often used as shown in *Fig.* 36.

The classification adopted is as follows[2]:—

Zone	Subzone	Stage
Dibunophyllum Zone (D)	D_3 Subzone of *Cyathaxonia*	Visean.
	D_2 Subzone of *Lonsdaleia floriformis*	
	D_1 Subzone of *Dibunophyllum* θ and ϕ	
Seminula Zone (S)	S_2 Subzone of *Productus cora* mut. S_2	
	S_1 Subzone of *Productus semireticulatus* ($C_2 + S_1 = \delta$)	
Syringothyris Zone (C)	C_2 Upper *Caninia* Beds	
	C_1 Lower *Caninia* Beds	Tournaisian.
	γ—opening phase of C	
Zaphrentis Zone (Z)	Z_2 Subzone of *Zaphrentis aff. cornucopiæ*	
	Z_1 Subzone of *Spirifer aff. clathratus*	
	β—opening phase of Z_1	
Cleistopora Zone (K)	K_2 Subzone of *Spiriferina* cf. *octoplicata*	
	K_1 Subzone of *Productus bassus*	
	K_m Phase of *Modiola lata*	

Fig. 36 shows the modern re-arrangement of these zones.

In the upper part of the Carboniferous Limestone—in the higher part of $D_{2\text{-}3}$—a special phase of sedimentation is sometimes developed. This is especially the case in Western Ireland, Isle of Man, North Wales, West of the Pennines and in Devon and Cornwall. The deposits comprise a series of shales, black limestones and sandstones. Conditions were favourable for the development of Goniatites (by which the beds are zoned), but inimical

[1] A. Vaughan, "The Correlation of Dinantian and Avonian," *Quart. Jour. Geol. Soc.*, vol. lxxi., 1915, pp. 1-52.

[2] A. Vaughan, *Rep. Brit. Assoc.* for 1909 (1910).

FIG. 33 (*continued*).

mate position of the shorelines at different periods (β, C_1 in part, δ and $D_{1\text{-}2}$) is shown. Arrows indicate direction of shift of coastline. The Ranges of Mountains shown on the land masses are only intended to indicate the main "grain" of the country. Some further details are included in the coastal outline of $D_{1\text{-}2}$ period in the Midlands (after *W. W. King*). It was a coast deeply indented by fiords; the lines of hills projecting as headlands are: A. Charnwood; B. Nuneaton; C. Lickeys; D. Swinford Crest; E. Wrekin; F. Longmynd; G. Berwyn Anticline. In the Lake District area, F-F-F are faults, the scarps of which held up the marine transgression.

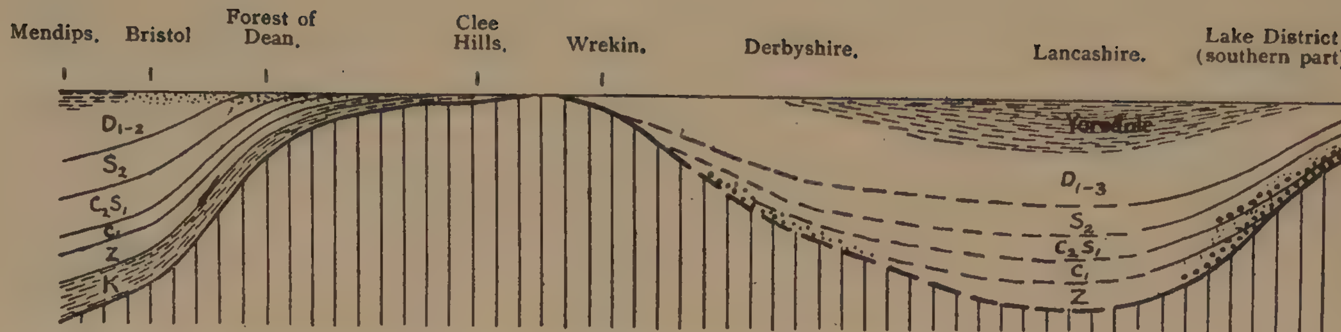

FIG. 34. Diagrammatic Section across the Carboniferous Limestone of England from South to North showing the two areas of deposition. The principal horizons of conglomerate, sandstone and shale are indicated; the unmarked beds are mainly limestone. Vertical Scale about 1 inch to 3,000 feet length of section approximately 220 miles. (*L.D.S.*) [Note: D beds probably attain a greater thickness in Derbyshire than shown.]

to the growth of the coral faunas of the normal Avonian. This is the Pendleside Phase, often distinguished by the letter p. Where deposits of D_3 times are represented by this type, they may be distinguished as "D_{3p}" and so on. The Yoredale Series (y) also occurs on the same horizon (see after, page 144).

The map (*Fig.* 33) and section (*Fig.* 34) show the movements of shorelines during the Carboniferous Period, and the section illustrates roughly the variation in thickness and lithology of the beds.

a. South-Western Province.

Perhaps the oldest marine Carboniferous Beds in England are those included as part of the Pilton Beds in North Devon. The lower part of these beds belongs to

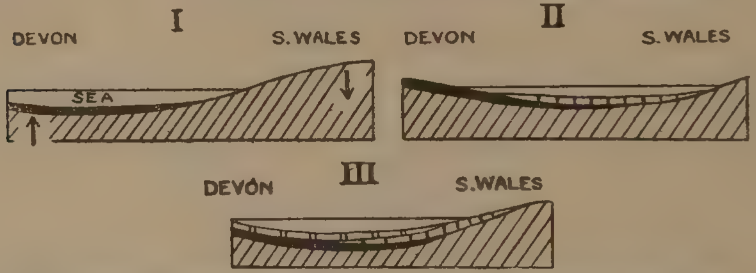

FIG. 35. Oscillations of land-surface during Carboniferous Limestone times in the South-Western Province. I, Early Carboniferous. II, End of Tournaisian. III, End of Visean. (*L.D.S.*)

the Upper Devonian, whilst fossils recorded from the upper part indicate a β horizon. The great Devono-Carboniferous transgression, to which reference has already been made, continued, and the sea invaded part of St George's Land to the north. But this was accompanied by a warping effect, so that the whole of Devon and Cornwall became land. Later a reverse warping action occurred, the sea retreated from St. George's Land, and at the end of Carboniferous Limestone times again invaded North Devon. An attempt has been made to illustrate these movements in the following diagram (*Fig.* 35). In North Devon, therefore, there is a strong unconformity between the Upper Pilton Beds and the succeeding Coddon Hill Cherts (D_3), which are followed by the Pendleside type of deposit.

The remainder of the South-western Province furnishes, in certain parts, a complete sequence of marine Avonian. The rocks are mainly calcareous, the limestones are all of shallow water type and are interrupted at intervals by "lagoon phases," comprising shales which seem to have been deposited in lagoons — stretches of salt-water in incomplete connexion with the sea — and which are characterized by the presence of *Modiola*. The limestones are frequently dolomitized, most frequently the change was contemporaneous. Oolitic limestones occur especially in C ("Caninia Oolite") and S_2. Some curious pseudobreccias in C_2 of Gower seem to be due to a partial recrystallization of a calcareous mud. Chert, appearing in λ and S_1, becomes important in the highest beds, just as it does in the Northern Province. Coarser, conglomeratic deposits are developed especially round the northern shoreline, and the sandstones come on at an earlier horizon in the north of the South-western Province than they do in the south. This points to an uplift along the southern side of St. George's Land, and the effect of this movement and of the curious "tilt" referred to above is seen in the presence of local unconformities, sometimes succeeded by a lagoon phase as in the Tenby area. Lagoon phases and contemporary dolomites become more numerous as one proceeds northwards and eastwards.

One of the most famous sections of Carboniferous Limestone is along the Gorge of the Avon near Bristol.[1] The section (*Fig.* 36) illustrates the lithology of the beds.

Some lavas of spilitic character, as well as coarser types, occur in the neighbourhood of Weston-super-Mare, and also in the "Lower Culm"—the name usually given to the representatives of the Carboniferous Limestone in that region—of Devonshire.

Concerning the fossils in the Carboniferous Limestone,[2] the

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[1] A. Vaughan, *Quart. Jour. Geol. Soc.*, vol. lxi. (1905), pp. 181-307. This is the classic paper in which the zoning of the Carboniferous Limestone was attempted. There is a good account of the present state of knowledge of the Limestone of the South-Western Province by T. F. Sibly, *Proc. Geol. Assoc.*, vol. xxxi. (1920).

[2] **The author is much indebted to the late Principal T. Franklin Sibly for suggesting this list of characteristic fossils and for other notes on the Carboniferous Limestone.**

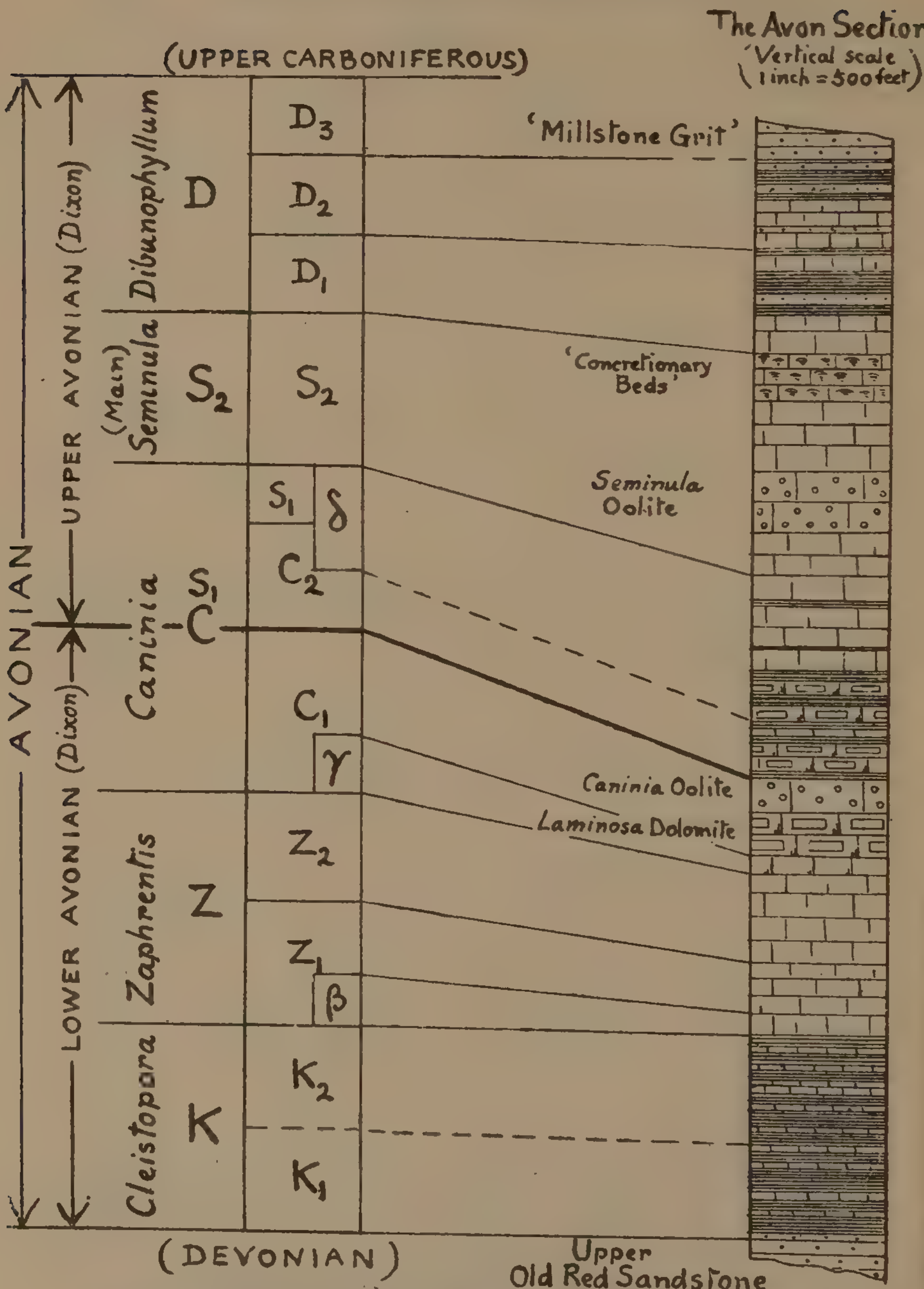

FIG. 36. Correlation of the Avonian Zone-scale with the Avon Section, Bristol. (*T. F. Sibly*, reproduced from *Proc. Geol. Assoc.*, vol. xxxi., 1920, by permission of the Council and of the Author.)

various horizons differ greatly in their abundance of fossils. When the limestone is dolomitised fossils are generally destroyed, and it frequently happens that an horizon which is richly fossiliferous in one locality is represented by unfossiliferous dolomite but a short distance away (*e.g.*, Barry, near Cardiff, fossiliferous series up to C_1; Taff Vale, Cardiff, largely unfossiliferous).

Cleistopora Zone; the zone fossil (*C.* cf. *geometrica*) is almost the only coral; brachiopods are numerous (*Productus bassus*, *Camarotæchia mitcheldeanensis* and *Chonetes hardrensis*). This zone is often represented by the Lower Limestone Shales and thin bands of limestone rich in crinoids may be present.

Zaphrentis Zone; *Zaphrentis* and the brachiopod *Spirifer clathratus*. In Z_1, *Zaphrentis delanouei* (β), *Z. omaliusi* and *Chonetes hardrensis*; in Z_2, *Z. omaliusi*, *Z. konincki* and *Athyris glabristria*.

Caninia Zone (C, including γ, and S_1); there is great variability in development and the southerly exposures are the more complete. *Caninia cylindrica*, *Syringothyris cuspidata* and large *Chonetes*. In γ, *Caninia cornucopiæ* and *C. patula;* in (C-S) *Cyathophyllum* and *Lithostrotion martini*.

Main *Seminula* Zone (S_2); *Lithostrotion martini*, *Seminula ficoides, Cyrtina carbonaria, Productus cora* (*corrugato-hemisphericus*) and *Chonetes papilionacea.*

Dibunophyllum Zone; *Dibunophyllum*, *Lithostrotion irregulare* and *Productus giganteus*. In D_1 also *Cyathophyllum murchisoni* and *Carcinophyllum vaughani;* in D_2 *Lonsdaleia floriformis* and *Cyathophyllum regium.*

b. Northern Province.

This area, which has been called also the North-west Channel, was scarcely defined at all in Lower Tournaisian times. The sea was then confined to a shallow bay in Ireland (unless the Pinskey Gill Beds—coastal beds in the Lake District—are of this age).[1] In C_1 times it spread eastwards and covered a part of the Isle of Man and filled up the Clitheroe depression and wrapped round the southern part of the Lake District. It seems that the Craven Fault (see page 175) had already been initiated, and the sea could not pass to the north of the fault-scarp.[2] Gradually, however, the sea did spread, invaded the southern part of the Lake District further to the north, and passed over the fault-scarp in δ times. It also spread over a

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[1] Possibly stretched across to Lancashire even in K times.

[2] This question has now been studied in detail by E. J. Garwood and E. Goodyear, *Quart. Jour. Geol. Soc.*, vol. lxxx., 1924, pp. 255-258.

considerable area south-eastwards, but only reached Derbyshire in S times, and attained its greatest extent in D_1-D_2 times. It is probable that the northern shores of St. George's Land were deeply indented by a number of fiord-like bays. In the same way the northern coast-line from the Isle of Man to the Lake District was almost certainly indented.

Derbyshire and the surrounding regions are remarkable for the great development—over 1,400 feet—of limestone, all of $D_{1\text{-}3}$ age. Basaltic lavas, including types rich in oligoclase which were mistakenly described as spilites, occur interbedded with the limestones in parts of Derbyshire. The lavas are locally known as "toadstones." Chert becomes increasingly important as one ascends the sequence in the Midland region.

Along the **northern borders of St. George's Land** all the subzones of D occur and a representative of S, and there is usually a great conglomerate (300 feet or more in thickness) at the base. It is of interest to observe that a continuation of the Berwyn Anticline interrupts these lower beds. Valuable cherts occur in the highest part as at Pentre, near Gronant. In **Anglesey** a coarse conglomerate and sandstones (600 feet) are followed by 700 feet of limestone ($D_{1\text{-}3}$). To the south the higher beds overlap on to the Archean. In the top of the Carboniferous Limestone—as in parts of South Wales also—pot-holes occur filled with Millstone Grit, indicating at least a local unconformity.

Passing to the opposite shores of the Northern Province, in the **Isle of Man** a massive conglomerate rests on Manx Slates, and is followed by limestones. Here lavas (basalts of Scottish type) are found. The beds which wrap round the southern part of the **Lake District** have been studied in great detail,[1] and include a complete succession from possibly Z_1 to D_3. Coarse coastal deposits are important in the lower part, and the beds over-

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[1] E. J. Garwood, *Quart. Jour. Geol. Soc.*, vol. lxviii. (1912), pp. 449-586. A comparative study of the succession here and in the S.W. Province will afford a valuable example of zonal differences in two areas of deposition only in indirect communication with one another.

lap and thin northwards against the Lake District rocks. In many of the limestones calcareous algæ are important as rock-formers. The series of zones which has been established for the Lake District differs somewhat from that in use in the South-western Province, as it is necessary to use different fossils as zonal indices, but the two provinces can be closely correlated. The absence of *Lithostrotion* in the lower Carboniferous Limestone is especially useful.

Towards the centre of the Northern Province, some remarkable features are to be observed, especially in the **Clitheroe** district (North Lancashire). The base of the limestone is nowhere seen, but the zones range down probably to Z and up to the junction of D_2-D_3 when a thick representative of the Pendleside phase follows (well seen on Pendle Hill). More important in the Clitheroe district are the "Reef-knolls"—semi-ovoid or hemispherical masses of limestone in which shells, especially brachiopods, are abundant and well preserved."[1] They have a somewhat special fauna and seem to be of the nature of shell-banks. They mostly occur in limestone of D_3 age, but may be found at other horizons. Physiographically they give rise to rounded knolls.

Passing to the **north-east of the Craven and Dent faults** (see page 169) a great change is observed.[2] These faults, though mainly Carbo-Permian in age, were probably initiated at an earlier date. Whether as a direct effect or only by coincidence, they mark the approximate junction between two very different types of deposit. The beds to the south and west have already been described; to the north-east there is a great series of limestones, sandstones and shales alternating with one another. The succession is well seen in the famous moorlands of Ingleborough. The most important bands of limestone (from the base upwards) are the Great Scar (600 feet), Hardraw Scar, Simonstone, Middle and Main Limestones. They seem to represent S and the whole of D. The beds above

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1 Somewhat comparable are the "Brachiopod-Beds" of the Midlands—lenticular beds, generally in D, in which brachiopods are extraordinarily abundant.

2 This question has been studied in detail by Prof. E. J. Garwood and Miss E. Goodyear, *op. cit. sup.* (1924).

the Great Scar Limestone—about 930 feet in all—are referred to as the Yoredale Rocks or Yoredale Series. They are succeeded by the Millstone Grit, yet curiously have an entirely different fauna from the Pendleside Series which occur at the same horizon, only a few miles to the South, on the other side of the Craven fault. Naturally this has given rise to much discussion. It seems that the Pendleside fauna is a "facies-fauna" developed only under special conditions, whereas the Yoredale rocks are but a sandy lateral variation of the normal Avonian (limestone) facies. They may be referred to as D_{2y} ; D_{3y} according to their age.

As one proceeds northwards into **Northumberland**[1] the beds gradually become more arenaceous, and indicate an approach to the Scottish (Highland Border) shoreline. In Northumberland the Lower Carboniferous Series is generally divided into :—

Bernician	Calcareous Division Carbonaceous Division (Scremerston Series)	"Carboniferous Limestone" Series of Scotland.
Tuedian	Fell Sandstone Series Cementstone Series	"Calciferous Sandstone" Series of Scotland.

THE CEMENTSTONE SERIES, best developed in the Tweed Valley, comprises sandstones and shales, with thin, fine-grained, magnesian limestones (Cementstones). The beds seem to have been laid down in fresh water, possibly in a lagoon. The area in which they occur is on the north-eastward continuation of the Lake District pre-Carboniferous ridge, and the Cheviot arm of the Devonian Lake Caledonia occupied at least part of the region. In other words, conditions were favourable for the formation of a shallow lagoon in early Carboniferous times. The fauna consists of land and fresh-water lamellibranchs and gastropods, fish, and arthropods such as crustaceans. Marine incursions at intervals are evidenced by the occurrence of brachiopods, such as *Syringothyris* and *Athyris*.

THE FELL SANDSTONES have a few bands of shale and one or two coal seams. They are said to yield the interesting fresh-water lamellibranch, *Archanodon jukesi*.

THE SCREMERSTON SERIES consists of sandstones, shales and coals—of the latter about six are of workable dimensions.

THE CALCAREOUS DIVISION comprises numerous bands of limestone, separated by sandstones and shales, with occasional coal-

[1] British Regional Geology: Northern England.

seams. Of the latter those in the little Lickar Basin are the most important.

The Northumbrian succession forms a natural transition between the Avonian of England and that of the Midland Valley of Scotland.

c. The Scottish Lowlands or the Midland Valley of Scotland.

This region is situated between the two great faults of Caledonian trend—already mentioned in connexion with the Devonian Basin—and is a true rift valley. Faulting originated during the Siluro-Devonian period of folding, but renewed movement along the same lines took place at intervals, especially at the end of the Carboniferous.

The Avonian, as mentioned above, comprises the CALCIFEROUS SANDSTONE SERIES below and the "CARBONIFEROUS LIMESTONE SERIES" (OF SCOTLAND) above.[1] The CALCIFEROUS SANDSTONE GROUP clearly corresponds to the Tuedian of Northumberland. It consists of clays and shales, with bands and nodules of clayey dolomite (cementstone) and with sandstones — especially in the upper part near Dunbar (=Fell Sandstones of Northumberland). Bands of marine limestone occur. Of these the Hollybush Limestone of the Glasgow district has yielded a D fauna. Separating the Glasgow and Lothian districts there is a ridge of Old Red Sandstone which runs across the valley and rises to the base of the Carboniferous Limestone Series.

The "CARBONIFEROUS LIMESTONE" or the UPPER SERIES of the Lower Carboniferous of Scotland is not only a misnomer — the beds are mostly sandstones and shales—but tends also to cause confusion since it is only equivalent to the upper part of the Carboniferous Limestone of England. It comprises

Upper Limestone Group,
Edge Coal Group,
Lower Limestone Group,
Midlothian Oil Shales.

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[1] J. S. Flett and others, "Geology of the District around Edinburgh," *Proc. Geol. Assoc.*, vol. xxv. (1914), pp. 1—40. J. W. Gregory and others, "Geology of the Glasgow District," *Proc. Geol. Assoc.*, vol. xxvi. (1915), pp. 151-194. These are very useful papers, summarizing and referring to original work.

The MIDLOTHIAN OIL SHALES (Carbonaceous Groups) are usually grouped with the Calciferous Sandstone Series, but they are probably equivalent to the Scremerston Series of Northumberland, as they include several small coal seams near Dunbar.

The LOWER LIMESTONE GROUP has a variable number of thin bands of marine limestone in the midst of a series of shales and sandstones.

The EDGE COAL GROUP—so called because of the steep, almost vertical, inclination on the western side of the Midlothian basin, and hence the coals are "on edge"—includes many important coals and valuable ironstones.

The UPPER LIMESTONE GROUP again includes several coal seams, the limestone bands are mostly thin, but are here remarkably constant. The name of one band—the Index Limestone—indicates the use to which it, together with some others, has been put.

The whole of the Carboniferous Limestone Series of Scotland probably corresponds to a high horizon in the Avonian of England—the greater part of D and the Pendleside Series.

CARBONIFEROUS VOLCANIC ROCKS OF SCOTLAND.[1]

The Carboniferous of the Midland Valley is further remarkable for including an extensive series of lavas and intrusive rocks belonging to the Alkaline or Atlantic Suite, and comprising a very interesting series of rock-types. They afford an attractive and easily-studied example of the sequence of events and variation of rock-types in a single Petrographical Province. Unfortunately there are no large plutonic masses. The igneous history of the period was briefly :—

1. Extrusion in Early Carboniferous Times.

The lavas are mostly basalts, together with trachybasalts, trachytes and trachytoid phonolites, as well as more acid types. The basalts may be divided into macroporphyritic and microporphyritic types. The important Macroporphyritic Basalts comprise :—

a. Craiglockart Type, with phenocrysts of olivine and augite.
b. Dunsapie Type, with phenocrysts of plagioclase, olivine and augite.
c. Markle Type, with phenocrysts of plagioclase (labradorite).

In the west the lavas form the great plateau called the Clyde Plateau—now much faulted—and elsewhere numerous ranges of hills. The vents can often be traced, and are frequently filled with agglomerate. Notable examples occur at Arthur's Seat, Edinburgh, and Meikle Binn, Campsie Fells. The lavas were all probably poured out in shallow water, and the passage of a lava just *under* the soft mud was often as easy as on its surface. Hence there are numerous sills, sometimes not easily distinguishable from lavas.

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[1] See references on page 145.

2. Slight Extrusion in Millstone Grit Times.

3. A Great Series of Alkaline Intrusions.

In the East (Lothians) the intrusions are intimately associated with the lavas, and are of more normal type than in the west (Glasgow), where they are later. The former are mainly dolerites, some allied to teschenites. The latter include types rich in analcite or nepheline, or both, and carry a characteristic purplish augite. Even when the analcite or nepheline is absent, the latter remains, and the colour is characteristic of an augite rich in Titanium, or having a high soda content. In the Glasgow District the rocks range from intermediate and basic rocks (analcite syenite, teschenites and theralites) to ultrabasic rocks (picrites). Some fine examples of composite sills occur, as at Lugar.

4. Renewed Extrusion in Late Carboniferous and Permian Times (the Mauchline lavas, etc.).

This series is closely associated with the alkaline intrusions. The rocks comprise basic basalts, rich in olivine, nepheline basalts and limburgites.

5. Numerous and often large E.—W. Dykes and Sills of Quartz Dolerite.

These rocks are petrographically very distinct from the earlier intrusions, and are apparently connected with the Carbo-Permian movements. The Great Whin Sill of Northumberland is doubtless one of the series.

d. Ireland.

Carboniferous Rocks, especially of the age of the Carboniferous Limestone, cover a very large part—approximately 2/3—of the surface of Ireland. All over the great Central Plain they are, however, largely hidden by drift, and detailed investigations have only been carried out over small areas. Briefly, one may summarize the accurate knowledge as follows:

1. In the north is a continuation of the Scotch facies.
2. In the east, near Dublin, the succession is comparable with that in the South-Western Province of England.[1]
3. Over the greater part of Central Ireland limestones are probably the predominant lithological type, but to the west and north — doubtless due to the existence of great land masses in that direction — arenaceous and argillaceous deposits become more important. The

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[1] At Rush, near Dublin, is found the typical development of a faunal type which is characterized by the great development of the coral *Cyathaxonia*. Comparable with the Yoredale and Pendleside phases, the *Cyathaxonia* phase may be distinguished by the letter x—thus D_2x, D_3x, etc.

"Carboniferous Slate," which comes below the limestones, and may be up to 5,000 feet in thickness, probably represents, at least in certain localities, the greater part of the Carboniferous Limestone of England.

4. There is a widespread development of the Pendleside phase.[1]

ECONOMIC GEOLOGY OF THE LOWER CARBONIFEROUS (CARBONIFEROUS LIMESTONE).

1. Building Stones. The Carboniferous Limestone is extensively used, but not so much in this country as elsewhere (in Belgium the "Petit granit" is used to an enormous extent). The stones used are mostly hard crinoidal or sometimes oolitic limestones; the dolomites to a less extent.

2. Road Stones. The limestone is largely used, but of greater importance are the igneous rocks of Carboniferous age—especially in the Midland Valley of Scotland (Lower and Upper Carboniferous). In England the "toadstones" of Derbyshire may be noted.

3. Lime and Cement. Both are important industries (*e.g.*, Derbyshire).

4. Sands, etc. Very pure sands—sometimes of doubtful age—occur in pockets in the limestone, especially in Derbyshire and Flintshire. Sandstones suitable for glass manufacture and for refractory purposes—soft and easily crushed—occur in the Lower Carboniferous of the Midland Valley. As refractory materials—for lining furnaces, etc.—the ganisters of the latter region are also important. In England dolomite of Carboniferous age is quarried for similar purposes. Note also the Pentre Cherts of North Wales used in the Potteries for grinding.

5. Clays. The fireclays of Scotland may be mentioned.

6. Oil Shales. An important and old-established industry in the Midland Valley is the production of oil from the destructive distillation of the oil shales. The shale is fed into retorts which are then closed (except for an outlet pipe) and heated to a certain temperature so that the oil is distilled off. Formerly a yield of up to 60 barrels of oil per ton of shale was obtained, but now, owing to the exhaustion of the best shales, 18 barrels a ton may be considered good. The by-products (especially Ammonium sulphate—manufactured from the ammonia produced—an important manure) have, in many cases, become more important than the oil. Broxburn, near Edinburgh, may be mentioned as an old and well-known centre of the industry.

7. Oil. Elaterite (Elastic Bitumen) and seepages of very heavy oily material or grease have long been known in some Carboniferous Limestone districts of Derbyshire, and a great amount of money has been spent in boring for oil. Oil was found (Hardstoft, Derbyshire), but it was not until the Second World War that an English oilfield which can be regarded as a commercial success was discovered.

8. Coal. Important in the Lower Carboniferous of the Mid-

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[1] See note on p. 147.

land Valley. The celebrated "Boghead Coal," consisting largely of spores, may also be noted. It occurs as a small seam at Torbane Hill, Linlithgow, and was the subject of a protracted lawsuit to decide whether it really was a "coal."

9. Iron Ores. Some of the most important masses of iron ore in these islands—such as the Hæmatites of Cumberland, South Wales, Forest of Dean, etc.—occur as pockets [1] in the upper part of the Carboniferous Limestone. They are to be regarded as metasomatic replacements of the limestone by ferruginous percolating waters, the iron in the latter having been obtained from the overlying (or formerly overlying) Permian and Triassic deposits. In some cases hæmatite has resulted, but frequently the iron carbonate, chalybite. The latter may have oxidized to limonite.

In connexion with the iron smelting industry the use of Carboniferous Limestone as a flux in various smelting operations should be noticed. Enormous quantities are consumed.

10. Metallic Minerals. Two of the most important are Lead and Zinc — usually occurring in association — in veins in the Carboniferous Limestone of Derbyshire.

11. Non-Metallic Minerals. Fluorspar is the common gangue mineral in the Derbyshire veins, and the prettily banded blue and purple variety known as "Blue John" is manufactured into small articles—paper weights, etc. Barytes also occurs.

12. Water Supply. The Carboniferous Limestone is an important water-bearing formation, but varies greatly in its yield. This is due to the fact that the water tends to follow large crevices and underground water courses, or to collect into underground reservoirs. The water is naturally very hard and deposits of calcareous tufa are usually to be found round springs. The extensive areas of Carboniferous Limestone in the Midlands form important catchment areas, but the construction of reservoirs is rendered very difficult owing to the fissured nature of the ground.

13. Scenery and Agriculture. *a* The Midland Valley of Scotland, owing to the peculiar nature of its Lower Carboniferous Rocks, stands apart from the other areas of the British Isles. It is in part a great coalfield and industrial region. *b*. Other regions of the British Isles. The Carboniferous Limestone districts are often some of the most picturesque in England, combining as they do great cliffs and gorges of bare grey limestone (Cheddar, Avon Gorge, Settle), with delightful wooded valleys (Derbyshire) and bleak upland moors (Derbyshire, Western Yorkshire, etc.). The patches of bare rock with rain-dissolved furrows (grikes) and the disappearing streams of the latter vie in interest with the pretty caverns with stalactites (Matlock) of the valleys. Sheep farming is usually more important than agriculture. The situation of several noted "spas" with medicinal springs—such as Matlock and Buxton—on the Carboniferous Limestone may be mentioned.

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[1] Sometimes they follow bedding planes in the limestone.

THE CARBONIFEROUS LIMESTONE IN BELGIUM.

The succession in Belgium is of great interest in a consideration of the British deposits. It occurs in the synclinoria of Dinant and Namur. Minor folding has resulted in extensive outcrops of the limestone, and magnificent exposures are visible in the deep river valleys—especially that of the Meuse. Certain points of interest may be noted in order :—

1. An exact correlation with England by means of zones is now possible.

2. Independent of the zonal divisions, which pass from one to the other, there are well marked divisions into lithological types or "facies." Of these the most important is the "Waulsortian," of which the most characteristic member is a limestone, with blue veins, abounding in Fenestellids, and in which brachiopods are locally abundant (Knoll-facies of England). Another interesting lithological type, mainly Tournaisian, is the well-known "Petit granit," a hard, crinoidal, dark limestone much used in building.

3. Just as in the South-Western Province of England there is an increase in dolomites northwards, so in the Namur synclinorium the great part of the sequence is represented by dolomites.

MILLSTONE GRIT PERIOD.
GEOGRAPHY OF THE PERIOD.

1. We have already noted in Lower Carboniferous times

a. the existence of a great land mass to the north and west;

b. the existence of a strip of land across England forming a barrier between the northern and southern stretches of sea;

c. the formation of shallow water limestones occasionally interrupted by "lagoon phases."

2. The Carboniferous Limestone or, where they occur, the Pendleside Beds are overlain by great masses of coarse sandstone ("grit"), with beds of shale, constituting together the Millstone Grit. These are the deltaic deposits of a great river which drained from the north. The geography of the time is illustrated in *Fig.* 37. Taking first the northern area, naturally the deposits thin southwards as shown in the section *Fig.* 38. They tail out and are absent in South Staffordshire, Warwickshire and most of the Shropshire Coalfields. In the southern area the so-called Millstone Grit is more of the nature of a coastal deposit round St. George's Land, and

FIG. 37. Map showing the probable distribution of Land and Water in the Millstone Grit Period (after *Gilligan*): A, River bringing schist from Blair Athol Region; B, River bringing porphyry from Oslo region (Norway); C, D, Rivers bringing sand, granite, etc.; E, River bringing granite, etc.; S, Line of Section. (Redrawn from the *Quart. Jour. Geol. Soc.*, vol. lxxii. (1918), by permission of the Council and of the Author.) [As an example of a river running out to sea and building up a "fingered" delta, compare the Mississippi.]

is partly of Lower Carboniferous age; in the same way the Millstone Grit of Scotland is a shore deposit along the great northern coastline.

3. A careful study of the Millstone Grit deposits has resulted in an extensive knowledge of the physical conditions prevalent at the time. The line of study and the results are outlined below.

4. It must be remembered that the "Millstone Grit Period" cannot really be separated from the Coal Measure Period, but it is convenient to consider them separately owing to the special and well-defined geographical conditions.

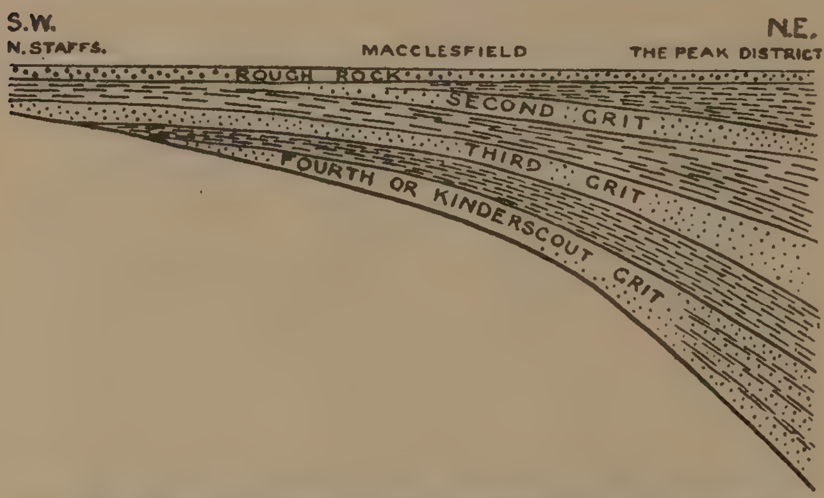

FIG. 38. Section across a small portion of the Millstone Grit Delta. Sediment coming from North-East. Length of Section about 25 miles. Vertical Scale about 1,600 feet to one inch (*L.D.S.*)

THE MILLSTONE GRIT IN ENGLAND.

I. Northern Area.[1]

As shown in the section (*Fig.* 38) the Millstone Grit comprises alternations of coarse sandstones and shales. The sandstones are pebbly, and the pebbles include

[1] This account is summarized from the important paper by Dr. A. Gilligan, *Quart. Jour. Geol. Soc.*, vol. lxxv. (1919-20), pp. 251-294. See also W. S. Bisat's important work on the goniatite zones of the Millstone Grit, *Proc. Yorks. Geol. Soc.*, 1924.

a. Quartz (abundant) largely derived from mechanically deformed rocks, and showing a mylonized structure.

b. Felspar mostly of fresh, pink coloured microcline or microcline microperthite.

c. Pegmatite of microcline and quartz, with undulose extinction.

d. Other Igneous Rocks, including two-mica granites and porphyries, which bear some likeness to rocks from the Oslo district.

e. Metamorphic Rocks; gneisses, mica-schists and quartz-schists. A pebble of distinctive chlorite-schist has been identified with rocks found in situ in the Blair Athol district.

f. Sedimentary Rocks, especially chert. One proved to be a silicified oolite, and resembles certain pebbles from the Torridon Sandstone. Masses of shale in the grit seem to have been derived from the contemporaneous denudation of layers of hardened mud.

An examination of the finer material of the sandstones and shales showed the presence of the following:

a. Quartz. Many of the grains show mechanical deformation, as if derived from gneisses and schists. Numerous inclusions occur.

b. Felspar. Microcline is predominant, and, except where surface weathering has taken place, is remarkably fresh.

c. Mica, not abundant except in the shales, where it is probably of secondary origin.

d. Heavy minerals. The most abundant are: Garnet, Rutile, Zircon, Tourmaline, Ilmenite and Monazite. Most of these minerals are of common occurrence in schists and granites, but the last mentioned, usually rare, has recently been found to have a wide distribution in the granites of Northern Scotland.

Regarding the origin of the sediments it follows that

a. The land mass from which they were derived consisted largely of crushed granitoid gneiss, ramified by veins of pegmatite and cut by masses of unaltered granite. Metamorphic rocks also occurred, together with some little-altered sediments which have yielded the chert. Scotland fulfils the requirements as the main source of origin.

b. The freshness of the felspar probably indicates the work of insolation—the sun's action on a rugged, bare land.

c The coarseness of the material points to elevation and a high mountain range giving rise to strong mountain torrents. Such a high land mass, heated by the sun's rays, would cause a monsoon, blowing from the south or south-east, just as Asia does at the present day, and this helps to explain the luxuriant coal measure vegetation which shortly afterwards flourished at its foot.

The marine fauna of the shales is not as a rule abundant. The most important types are Goniatites (*Glyphioceras*, etc.). See also later.

II. Southern Area.

In the South Wales Coalfield there is evidence that in places the Millstone Grit rests unconformably on the Carboniferous Limestone, and there are "pot-holes" in the upper surface of the latter. The Millstone Grit consists of a basal conglomerate, succeeded by shales with marine fossils, followed by sandstones (Farewell Rock). In Gower the Millstone Grit is almost wholly represented by shales.

III. Scottish Area.

The Millstone Grit is represented by part of the Roslin Sandstone as described elsewhere (page 162).

THE COAL MEASURE PERIOD.
GEOGRAPHY OF THE PERIOD.

1. The silting up of the Lower Carboniferous sea by the masses of sediment which make up the Millstone Grit prepared the way for the luxuriant growth of swampy forests which characterize the Coal Measure Period.

2. Like the great rivers of the present day, the Millstone Grit rivers must have built up a broad delta but a few feet above sea-level. Heavy monsoon rains encouraged the growth of great forests, and the greater part of the surface of England was converted into a low-lying forested swamp.

3. At different times and in different areas, these forests were overwhelmed by masses of sediment brought down by the rivers. Subsidence went on periodically, new forests sprang up, only to be overwhelmed by fresh sediment. Sometimes the subsidence was local, so that, whilst the growth of a forest was continuous in one area (giving a thick seam of coal), elsewhere it was interrupted by the deposition of a mass of sand, and two coal seams occur in the place of one. Lithologically the Coal Measures consist of great thicknesses of sandstones and dark shales, in which the coal seams themselves are but minor episodes.

4. At other times small but more general subsidences took place and the sea flowed over the greater part of the huge swamp, giving rise to thin but persistent marine bands which can be traced over wide areas, and which afford valuable datum lines in correlation.

5. The main regions which remained land in the British Isles were

a. The great mainland to the north and west;
b. The central ridge of St. George's Land, including Central Wales;
c. A small portion of the Southern Uplands.

6. The source of the material of the Coal Measure Sandstones has not been investigated in the same way as it has been for the Millstone Grit; they were probably derived from the same source, together with a less important quota of sediment brought in from the west.

7. Various phenomena connected with differential subsidence can be traced in Coal Measure rocks. Contemporaneous denudation giving rise to clay-pebble and claystone conglomerates is often well marked. The distribution of vegetation is also interesting; an area which at one time might be suitable for the growth of certain groups of plants at other times was more favourable for other groups.

8. It should be noted that, in general, a seam of coal is underlain by a "fire clay," which represents the muddy ooze in which the plants grew.

9. Towards the close of Coal Measure times in England arid, desert conditions began to set in. They commenced in the north and gradually worked southwards.

10. The Carboniferous Period was brought to a close by a great series of widespread earth-movements. Just as with other great periods of orogenic disturbance, the folding movements commenced gradually. One of the results of the Carbo-Permian folding was the rise of the Mercian Highlands across Central England. They commenced to arise at least early in Carboniferous times, and in South Staffordshire the Middle Coal Measures are banked up against the ridge. Concurrently there was a long, slow movement of subsidence to the north, so that the greatest thickness of Coal Measures occurs in a belt

running approximately east and west through Lancashire (see section, *Fig.* 40).

COAL MEASURES IN THE BRITISH ISLES.

I. Introductory.

Considerable difficulty has been experienced in the classification of the Coal Measures, and different schemes have been devised using different groups of organisms as the basis of correlation.[1] In many cases important considerations have been ignored :—

a. Classification by plants. The plant remains at various horizons depend to some extent on ecological conditions, *i.e.*, the conditions prevalent in the particular areas in which the plants grew.[2] Classification by plants gives broad divisions rather than "zones," although zones have been widely used on the Continent, and they have been proposed for the English Coal Measures by Miss E. Dix.

b. Classification by fresh-water molluscs (lamellibranchs). Lamellibranchs are very abundant in the Coal Measures, but owing to their great variability have presented some difficulty in correlation. Prof. A. E. Trueman, however, has devised a series of zones which has made possible the correlation of the coalfields of England and Wales.

c. Classification by marine organisms. Marine bands are usually thin and few in number, hence they form valuable datum planes; but the marine organisms cannot be used for the zoning of the Coal Measures as a whole owing to their rarity.

The only really satisfactory classification must be one which takes account of all the faunas and floras. For the sake of reference such a classification is set out in tabular form on page 157.[3]

The present distribution of the Coal Measures into separate "coalfields" is shown in the map, *Fig.* 39. The northern fields, between the Scottish Land mass and St. George's Land formed one area of deposition; south of St. George's Land another.

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[1] So important is the correlation of Carboniferous rocks, that a special international congress (Congrès de stratigraphie carbonifère) exists to study the subject.

[2] D. Davies, *Quart. Jour. Geol. Soc.,* vol. lxxvii. (1921), pp. 30-74.

[3] Based on the works of Prof. A. E. Trueman and Miss E. Dix.

CLASSIFICATION OF THE COAL MEASURES (WESTPHALIAN, *sensu lato*).

	Kidston's Floral Divisions	Main Characters of Floras	Plant Zones (Dix)	South Wales	North Staffs	Freshwater Shells (Davies & Trueman)
UPPER WESTPHALIAN	Radstockian[1] or Upper Coal Measures with Fourth Flora	Abundance of *Pecopteris* (*P. arborescens* and *P. polymorpha*), *Alethopteris serli*, *Neuropteris rarinervis*	*Pecopteris lamurensis*, etc *Mixoneura ovata*, etc.	Upper Coal Series	Keele Series	Zone of *Anthraconauta tenuis*
	Staffordian or Transition Coal Measures with Third Flora	Mixture of Second and Fourth Floras	*Neuropteris rarinervis*, etc.	Pennant Grit Series	Newcastle-u.-Lyme Group Etruria Marls Blackband Group	Zone of *Anthraconauta phillipsi*
MIDDLE WESTPHALIAN	Westphalian (*sensu stricto*) or Middle Coal Measures with Second Flora (=Yorkian)	*Sigillaria* abundant (especially *S. boblayi*), also *Calamites* and *Sphenophyllum*; *Sphenopteris* & *Neuropteris* reach maximum	*Neuropteris tenuifolia*, etc. *Lonchopteris rugosa*, etc. *Alethopteris lonchitica* *Neuropteris schlehani* and *Lyginopteris hoeninghausi*	Cwmgorse Marine Beds Cefn Coed Marine Beds Lower Coal Series	Bay Mine Marine Horizon Gin Mine Marine Horizon Middle Coal Measures	Zone of *Carbonicola similis* and *Anthracomya pulchra* Zone of *Anthracomya modiolaris* Zone of *Carbonicola* ~~*ovalis*~~ communis
LOWER WESTPH	Lanarkian or Lower Coal Measures and Millstone Grit with First Flora	*Lepidodendron* abundant, also *Calamites* (*C. suckovi* and *C. ramosus*). *Sigillaria* rare. *Alethopteris* (*A. lonchitica* and *A. decurrens*) and *Sphenopteris* are the dominant fern-like plants	*Pecopteris aspera*	Millstone Grit	Lower Coal Measures Millstone Grit	Zone of *Anthracomya lenisulcata*

[1] The Radstockian, including the Radstock Series of Somerset and the almost unfossiliferous red Keele Series of the Midlands, may be Stephanian and not Upper Westphalian.

II. Coalfields of the North and Midlands of England.

The Coal Measures were probably deposited over the whole of the area from the Scottish Highlands Land mass to St. George's Land in Central England. The Southern Uplands may have formed an interruption, as in the Douglas Coalfield the Coal Measures seem to occupy a pre-Carboniferous hollow in the rocks of the Southern Uplands. Later earth-movements and consequent denudation have resulted in the present distribution of the Coal Measures in a number of isolated basins. The more important folds are

(i) A complex north and south anticlinal known as the Pennine Axis giving an eastern and a western group. The eastern includes the fields of Northumberland, Durham, Yorkshire, Nottingham, Leicester and Warwick. The western embraces the fields of Cumberland, Lancashire, Cheshire, North Wales, Staffordshire (North and South) and the smaller fields of Shropshire, etc.

(ii) West and east folds. A northern one—the Howgill Anticline, separates the Cumberland, Northumberland and Durham fields from those to the south. Another cuts off the areas of Shropshire, South Staffordshire, Warwick and Leicester from those on the north — North Staffordshire, Nottingham and Yorkshire.

Further details of the folds and the faults which affect the Coal Measures are given in the account of the Carbo-Permian earth-movements.

1. The Lower Coal Measures (Lanarkian) are unproductive, consisting of hard grey flagstones with bands of shale. Marine bands are numerous and plants are frequently only abundant in the neighbourhood of the few thin coal seams. Those beds are thickest in the central regions (North Staffordshire, South Lancashire, etc.). To the south they thin out rapidly against the old ridge running from South Staffordshire through Charnwood to Nuneaton, and are absent in South Staffordshire, Warwickshire and Shropshire (Coalbrookdale, southern part). Similarly the Lower Coal Measures thin to the north in Cumberland and Northumberland. The Lower

FIG. 39. The Coalfields of the British Isles. Exposed coalfields in solid black, concealed coalfields (approximate) dotted. ENGLAND: 1, Northumberland and Durham; 2, Cumberland; 3, Ingleton; 4, Lancashire; 5, Yorks, Notts and Derby; 6, North Staffordshire Fields; 7, North Wales Fields; 8, Shropshire (Shrewsbury); 9, Coalbrookdale; 10, Forest of Wyre; 11, South Staffordshire; 12, Leicestershire; 13, Warwickshire; 14, Pembrokeshire; 15, South Wales; 16, Forest of Dean; 17, Somerset and Gloucestershire (Nailsea, Radstock and Bristol); 18, East Kent. SCOTLAND: 1, Fifeshire; 2, Midlothian; 3, Clackmannan; 4, Central (Lanark); 5, Ayrshire; 6, Douglas (Lesmahagow); 7, Sanquhar; 8, Canonbie (partly in England). IRELAND: 1, County Tyrone; 2, Ballycastle; 3, Connaught; 4, West Munster; 5, East Munster; 6, Leinster (Castlecomer). (*L.D.S.*)

For full details reference should be made to "The Coalfields of Great Britain" edited by Sir A. E. Trueman (*Arnold*, 1954).

Coal Measures are often known as the Ganister Measures from the abundance of ganister, a hard, siliceous underclay which forms the floors of the coal seams or occurs as separate bands. The fauna and flora are roughly indicated on the tabular classification. Of the marine horizons those of " Frog's Row " and " Gin Mine " have been traced over wide areas, and can be correlated with similar marine bands on the Continent (Northern France and Belgium). As a rule the marine fossils belong to species common to the Lower Carboniferous, the most distinctive being certain goniatites. Small species of *Chonetes* and *Productus* occur, with lamellibranchs, such as *Posidoniella* and *Pterinopecten papyraceus*, and a few gastropods. *Lingula* (*L. mytiloides*) often occurs in great profusion, and may indicate brackish water. The marine fossils never occur in the same beds as the freshwater, of which *Carbonicola* is the most important member. For the plants see the correlation table.

2. THE MIDDLE COAL MEASURES (YORKIAN)[1] are the most important division commercially, and have numerous seams of coal. They have a wider extension than the Lower Coal Measures and overlap them. Again they are thickest in the central regions, especially in Lancashire, and thin southwards. This is illustrated in the diagrammatic section (*Fig.* 40). From 3,500 feet in Lancashire they are reduced to 1,600 in North Staffordshire and 500 in South Staffordshire. This is largely the effect of subsidence in the north and uplift (rise of the Mercian Highlands) in the south. One interesting result is that some fourteen seams of coal when traced southwards coalesce into a single seam—the celebrated Thick Coal. In South Staffordshire only about 100 feet of strata underlie the Thick Coal; at the base is a conglomerate resting unconformably on various older rocks. The evidence shows that, before Middle Coal Measure times, not only had the ridge of the Mercian Highlands (*i.e.*, the barrier or St. George's Land of Lower Carboniferous) begun to rise, but that it was crossed by a series of folds with a Charnian or Cale-

[1] To avoid confusion between Westphalian *sensu lato* and Westphalian *sensu stricto* the term " Yorkian " has been proposed in place of the latter and will be adopted here.

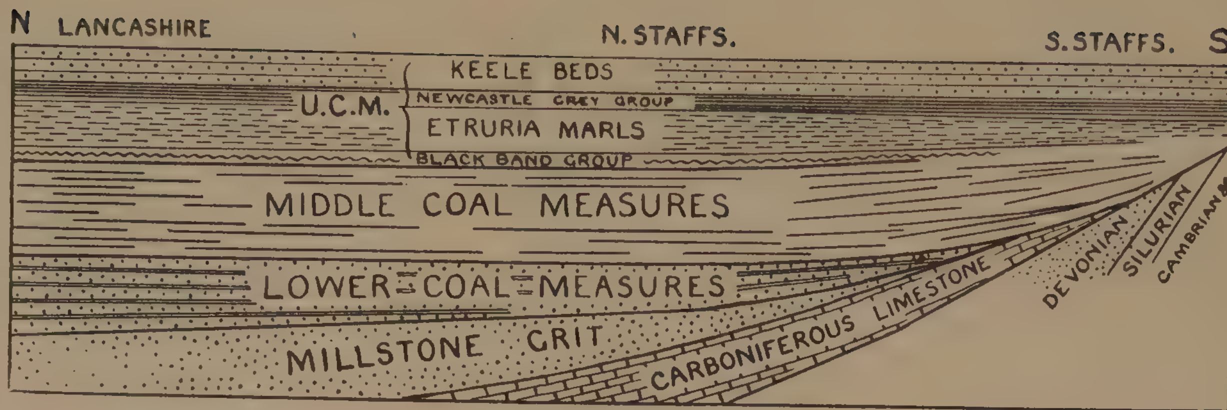

FIG. 40. Diagrammatic Section across the Coal Measures of the North and Midlands. This section shows not only the southward thinning of the beds, but also the gradual uplift of the "Mercian Highlands" in the South. They form a ridge against which the Carboniferous Limestone, the Millstone Grit, Lower, Middle and Upper Coal Measures all tail out, yet it was not until the end of the Carboniferous Period that they were uplifted into a mountain range. Length of section about 90 miles; Vertical Scale, 1 inch to 6,000 feet. (*L.D.S.*)

donian trend (see *Fig.* 33), and had been both faulted and denuded. After the deposition of the Coal Measures folding and faulting continued along the same lines, and the Thick Coal is affected by two series of folds having Charnian and Caledonian trends.[1]

To the north the Middle Coal Measures maintain a considerable thickness (2,000 feet in Durham), but thin to under 1,000 in Cumberland. Marine bands are far less frequent in the Middle Coal Measures. The freshwater fauna includes notably *Carbonicola*, *Anthracomya*, and *Naiadites*.

3. TRANSITION AND UPPER COAL MEASURES (STAFFORDIAN and RADSTOCKIAN).—It is in this series that the oncoming of desert conditions can be traced. In the little Canonbie Coalfield these beds are represented by red and purple sandstones, in Cumberland the same is true. In North Staffordshire (see table) the Keele Beds consist of red and purple sandstones and marls, the Etruria marls are also red or purple, whilst the intermediate Newcastle Beds are grey. The presence of thin bands of *Spirorbis* Limestone is a constant feature in the Upper Coal Measures (in the Keele Beds and in the Red Beds of Cumberland and Canonbie). The most notable freshwater fossil is *Anthraconauta phillipsi*.

III. Coal Measures of Scotland.

In the Midland Valley of Scotland certain sandstones (Roslin Sandstone) occur on the same horizon as the Millstone Grit of England. From a study of both the fish-remains and the plants it has been shown that two divisions can be distinguished, a lower which must be linked with the Avonian and an upper which forms the base of the Westphalian.

The productive Coal Measures of Scotland (apart from the coal-bearing Lower Carboniferous already mentioned) are Lanarkian and Yorkian in age, corresponding to the Lower and Middle Coal Measures in England. They

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1 W. W. King, Report British Association for 1916 (Section C, Geology) and *Trans. Inst. Mining Eng.*, vol. lxi. (1921), pp. 151-168.

yield *Neuropteris heterophylla*, *N. gigantea*, etc., and have several marine bands. The Yorkian is succeeded by a great thickness of barren red sandstones and shales. These probably represent the Staffordian and the Radstockian. A Radstockian flora, in which *Anthraconauta phillipsi* also occurs, has been detected in Ayrshire.

IV. Coal Measures of South Wales, Bristol, etc.

In the South Wales field the Coal Measures fall into three lithological groups:—

Upper Coal Series,
Pennant Grit,
Lower Coal Series.

Most of the coal is obtained from the Lower Series and the Pennant Grit gives rise to the wild barren moorlands which separate the densely populated narrow valleys. Though so well marked lithologically, the Pennant Grit is not always on the same horizon. In the west it is Staffordian, in Glamorganshire (East) some productive Staffordian measures occur below the Grit, in the Bristol and Somerset coalfield the Pennant Grit occurs high up in the Staffordian. Just as in Belgium, Northern France, Kent and Staffordshire there is a marine horizon sometimes present which seems to separate the Lanarkian and Yorkian. The succession in the Swansea area may be summarized:—

Upper Coal Series		Radstockian
Pennant Grit	upper part	Radstockian
	lower part	Staffordian
Lower Coal Series	upper part (sandstones)	Staffordian
	lower part (the bulk of the series), shales with coals and ironstones, and several marine bands	Yorkian ? Lanarkian

At the base of the Staffordian is a conglomerate which includes pebbles of coal, showing that seams of coal had already been formed and denuded. There is a marked palæontological break between the Yorkian and Staffordian in East Glamorgan, 58 species of plants

are common to the two, 49 occur in the Yorkian alone and 47 are confined to the Staffordian,[1] in which a still more notable faunal change also occurs.[2]

The Coal Measures reach a great thickness in South Wales—over 8,000 feet—and the seams comprise household (humic), anthracitic and steam coal. Just as the Coal Measures of the northern region overlap one another on to the old ridge of St. George's Land, so they do in the southern region. In the Forest of Dean Coalfield the whole coal-bearing series belongs to a high horizon, it rests with marked unconformity on the Millstone Grit in the south, but passes northwards on to the Carboniferous Limestone and the Old Red Sandstone.

The Somerset and Gloucester Coalfields, whilst not of great importance commercially, are of interest as exhibiting some of the highest fossiliferous Coal Measures in the British Isles; the Radstock Series possibly being equivalent to part of the Lower Stephanian of the Continent. The general sequence is :—

Radstock Series = Radstockian.	
Barren Measures	?Staffordian.
Farrington Series	
Pennant Sandstone	
New Rock Series	
Vobster Series = ?Yorkian.	
Millstone Grit.	

Marine bands occur in the Vobster Series, and form useful horizons in general correlation.

V. Coal Measures in Kent.

If the mantle of Mesozoic rocks were stripped off East Kent and the Palæozoic Platform exposed, it would be found to consist of a series of beds dipping south-

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[1] D. Davies, *Op. cit.*

[2] A. E. Trueman, *Geol. Mag.*, 1929, p. 495.

wards, so that the oldest rocks (Carboniferous Limestone) occur in the north (under the Isle of Thanet) and younger rocks towards the south (see *Fig.* 40C, p. 174). The coal-measure succession may be summarized :—

Radstockian (lower)	= Keele Group of Staffs.
Staffordian Yorkian	= Newcastle Group. Etruria Group. Blackband Group.

The Lower Coal Measures or Lanarkian are unknown.

All three horizons of the Coal Measures have workable seams of coal. The existence of a hidden coalfield under Kent or the South-East of England had long been inferred from geological reasoning. It forms one of a chain of basins from Pembrokeshire to Germany, following the line of a great west to east Carbo-Permian Synclinal. The Kent Coalfield is bounded on the west by a sharp anticline or monocline running roughly north and south a short distance to the west of Canterbury. The mantle of Mesozoic rocks, as will be detailed later, thickens rapidly from the north (where it is less than 1,000 feet) to the south.

VI. Coal Measures of Devon and Cornwall.

The Coal Measure rocks of this area are barren as far as coal seams are concerned. They consist of fine-grained sandstones and shales in alternating bands, much folded and faulted. Occasionally there are thin bands of crushed coal (often called " culm," hence the name Culm Measures for these Cornish rocks) and layers of calcareous nodules. The latter have yielded a marine fauna of Goniatites and some lamellibranchs which seem to indicate a Lower Coal Measure age; the plants, however, point rather to a Middle Coal Measure age. There are no representatives of higher beds. Towards the south, a conglomerate at the base of the Coal Measures seems to overstep the Lower Carboniferous Beds on to the Devonian,

VII. Coal Measures in Ireland.

Whilst Coal Measures occupy not inconsiderable areas in Ireland, as coalfields they are unimportant. The West Munster Field is the largest in area, but the Lower Coal Measures, which occupy the greater part, are marine and yield little coal. In the north-east (Ballycastle and County Antrim) coal occurs in the Lower Carboniferous, in a position comparable with the Edge Coal Group of Scotland.

CONTINENTAL COAL MEASURES.

On the Continent the Coal Measures are divided into
Stephanian,
Westphalian.

It has been thought that the lower part of the Stephanian was represented in England; plants with Stephanian affinities do occur in the Upper Coal Measures of Bristol, but in the Upper Westphalian of Northern France there are also plants with Stephanian affinities. Whilst desert conditions prevailed in England and the Carbo-Permian uplifts had commenced, circumstances were still favourable for the growth of forests and the formation of coal seams further south on the Continent of Europe. The Stephanian rocks were sometimes laid down in isolated basins, showing that the Carbo-Permian folding had commenced there also.

THE ORIGIN OF COAL.[1]

Nearly all authorities are agreed that coal has resulted from an accumulation of vegetable matter, but much discussion has taken place as to details. The most generally accepted views are as follows :—

1. A forest, most nearly comparable with the Nipa-palm or mangrove swamps at the estuaries of modern tropical rivers flourished over great swampy areas. The roots of the trees were fixed in a muddy ooze which now forms the underclay of the coal seam. As the fronds, leaves or whole plants died and fell into the swamp they came under the action of bacteria, and all but their hardest tissues were converted into a homogeneous, probably jelly-like mass. By some slight earth movement or change in the course of the main river the forest was overwhelmed by masses of sediment, and the accumulation of decayed vegetable matter, by loss of moisture and gases, and under a little pressure, rapidly became converted into coal.
2. In a few cases great mats of vegetation, drifted down by the river, have helped, or, perhaps, are largely responsible for the material which has been transformed into coal.

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[1] See A. Raistrick and C. E. Marshall "The Nature and Origin of Coal and Coalseams," London, 1939.

3. In some cases the spores and spore cases of Lycopodiales, etc., form the bulk of the material. This is the case with Cannel coal.
4. In other cases some difference in original material, and probably in conditions of formation, have resulted in a seam of anthracite and not of ordinary household or steam coal.
5. In a few cases terrestrial accumulations of peat may have supplied the material.

ECONOMIC GEOLOGY OF THE UPPER CARBONIFEROUS (MILLSTONE GRIT AND COAL MEASURES).

1. Building Stones. The Upper Carboniferous is by far the most important source of sandstones in the country. The Millstone Grit is usually too soft, pebbly or felspathic to form a good building stone, but more locally—especially in parts of Yorkshire—it is excellent and largely used all over the country.

Some of the Coal Measure Sandstones furnish good stone, especially the Lanarkian of Yorkshire and Lancashire and the Pennant Grit of South Wales. Bricks are largely manufactured from the associated clays, and the stone becomes of less importance than would otherwise be the case.

2. Road Stones. More important than the sandstones—which are used—are the igneous rocks either of Carboniferous age or intruded into series of that age. In the Midland Valley of Scotland the lavas and intrusive rocks are both used, especially important being the late intrusions of Quartz-dolerite. Curb-stones and setts of the Aberdour (Fifeshire) rock may be found all over England. In the North of England the Great Whin Sill of the same age is important. In the Midlands the dolerites (of doubtful age) of Rowley Regis (near Birmingham) and especially of the Clee Hills ("dhu-stone") give rise to an enormous industry. (See also page 298.)

3. Sands. Many of the Coal Measure Sandstones are very pure, and, when crushed, furnish sands suitable for glass manufacture. (Yorkshire and the Midland Valley.)

4. Ganister. As a refractory material is of great importance. Obtained principally from the Lower Coal Measures. Some quartzitic sandstones of the Millstone Grit furnish world-famous refractory material (Dinas, South Wales).

5. Clays. Two distinct types may be separated :—

a. *Laminated Clays*—largely used in local brick-making.

b. *Fireclays.* Pure white or grey clays, which form the underclay of coal seams. Valuable for the manufacture of refractory goods. The less valuable burn to red (often with grey spots, due to the presence of iron sulphide): the more valuable to paler colours. The former furnish fine red engineering bricks, the latter fire-bricks, sanitary ware and glazed bricks or blocks for architectural purposes. Staffordshire has some of the best fireclays, whilst Yorkshire is an important centre for the manufacture of sanitary ware. The Midland Valley also has good fireclays.

6. Coal. The yearly production of coal in the British Isles is somewhere in the neighbourhood of 220,000,000 tons—a production which is second only to that of the United States. Practically the whole of this comes from Carboniferous Rocks, and that, with the exception of some of the Scottish production, entirely from the Coal Measures. The coals from the different fields vary in character, and consequently in the uses to which they are put :—

Anthracite is found exclusively in South Wales—especially in Pembrokeshire. It is hard, lustrous, does not soil the fingers, is not readily ignited, and has a higher percentage of fixed carbon than other coal. These qualities were formerly thought to be due to metamorphism—greater pressure, etc.—but are now believed to be due to a difference in composition of the mother substance.

Steam Coals, as their name implies, are used for the production of steam power in locomotives and boilers. Some of the best qualities are from South Wales.

Household Coals. Some of the best are furnished by Northumberland and Staffordshire.

Cannel Coal is a curious variety of coal occurring as small lenticles. It is dull, but takes a high polish, and consists largely of spores in a matrix or "Sapropelic jelly" of decomposed vegetable matter. Wigan (Lancashire).

7. Ironstone. The nodules of clay-ironstone, found commonly in Coal-Measure clays, were formerly collected, but at the present day the old iron-smelting industry is carried on in the same localities with imported ores (South Wales). The Black-Band Ironstones (Staffordshire and Scotland) were formerly of considerable importance.

8. Water Supply. The wild moorlands of Millstone Grit (Yorkshire, the Peak Country, etc.) form important catchment areas, and reservoirs have been constructed for the supply of several large towns. The Coal Measure sandstones yield chiefly local supplies.

9. Scenery and Agriculture. The Millstone Grit, as well as the more important sandstones of the Coal Measures (Pennant Grit of South Wales) form upland tracts of sparsely populated moor, often in strange contrast with the neighbouring coal bearing areas. Most of the great industrial areas of the British Isles are on Coal Measures or centred on hidden coalfields. It is superfluous to describe the former dreariness of the "Black Country." With the exhaustion of the coal here the country has taken on a new look. Even when the air is clean the Coal Measure Shales furnish a dirty-looking hungry clay soil—which, incidentally, benefits by admixture with the poor light soil furnished by the sandstone—in itself far from picturesque.

LIFE OF THE CARBONIFEROUS PERIOD.

In most respects the Lower Carboniferous, with its marine fauna, is very distinct from the Upper, with its continental fauna and flora. As a whole the period is characterized by the great development of ferns and fern-like, seed-bearing plants (Pteridosperms), the rise of amphibians and the profusion of spire-bearing (spiriferid) and productid brachiopods. Certain groups

of corals are also characteristic. The last English trilobite is found in the Millstone Grit.

a. Plants. Mostly Pteridosperms, with a few true ferns. It is often difficult to ascribe the remains of fronds or fructifications to the correct stems and roots, and different parts of the same plant have received separate names. Thus *Stigmaria* is the root portion of a large number of plants whose stems are known as *Sigillaria* and *Lepidodendron*, and whose fronds or leaves have again other names. From a stratigraphical point of view, impressions of plants are important, but the palæobotanist is more interested in the petrified remains—such as those found in beds of ash at Pettycur, Fifeshire, or in the "Coal-balls" of Lancashire and Yorkshire. The internal structure can be studied in such petrified plants. Besides the four floral groups of the Upper Carboniferous, the plants of the Lower Carboniferous form a distinct group. The luxuriance of Carboniferous vegetation must not be taken to indicate tropical conditions. Calcareous Algæ (*Solenopora, Mitcheldeania*) are important rock formers in the Avonian.

b. Vertebrata. Fish are fairly abundant in the Upper Carboniferous but have been little used in stratigraphical studies Amphibia are the most important of the larger vertebrates.

c. Arthropoda. The appearance of primitive insects in the Coal Measures is of great interest. The last British trilobites (*Phillipsia, Brachymetopus*) occur in the Avonian and Millstone Grit. *Estheria*, *Leaia* and their allies are important in the Coal Measures.

d. Mollusca. The Lamellibranchs of the Carboniferous Limestone are not important, with the exception of *Modiola*, which characterizes the lagoon phases, and a few, such as *Conocardium*, associated with brachiopods in the more normal limestones. In the Coal Measures they are of paramount importance, both in the marine bands (*Posidoniella, Pterinopecten*, etc.), but also as constituting the most noteworthy members of the fresh-water fauna (*Carbonicola, Naiadites, Anthracomya*). Among Gastropods the increase in siphonostomatous forms is to be noted. The Cephalopods include a few surviving forms of straight nautiloids (*Orthoceras*), but of paramount importance in the Avonian deposits of Pendleside type, in the Millstone Grit and in the Coal Measures (marine bands) are the primitive Ammonoids, the *Goniatites*.

e. Brachiopoda. These are of zonal value in the Lower Carboniferous, and include especially spiriferids (*Spirifer*), *Syringothyris* and its allies, the productids (*Productus*) with their markedly convex and concave valves, and numerous species of *Chonetes*. Terebratulids (*Dielasma*) become common. The abundant *Lingula* (*L. mytiloides*) of the marine bands in the Coal Measures should be noted.

f. Polyzoa. Abundant in certain bands of the Carboniferous Limestone.

g. Echinodermata. Crinoids are very abundant, and a crinoidal limestone is often the dominant lithological type of the

Avonian. Blastoids (*Pentremites*) are typically Carboniferous, though not abundant in England. Primitive Echinoids are fairly common.

h. Cœlenterata. Corals are of great zonal importance in the Carboniferous Limestone, and a great variety of types occur. The tabulate corals, represented by *Syringopora* and *Chætetes*, are insignificant compared with the numerous rugose forms—*Caninia*. *Cyathophyllum*, *Dibunophyllum*, *Lonsdaleia* and *Zaphrentis*, as well as the great generic group, *Lithostrotion*, with small laterally flattened true columella.

i. Protozoa. Foraminifera occur in rock-forming numbers in the Carboniferous Limestone (*Saccamina carteri*, *Endothyra* and *Fusulina*).

CHAPTER X.

THE CARBO-PERMIAN[1] EARTH-MOVEMENTS AND VULCANICITY.

Towards the close of Carboniferous time, a period of considerable folding commenced. By reference to British deposits most of the movements may be described as Post-Carboniferous and Pre-Permian. Thus, as shown on the map (page 176), most of the British Permian rocks rest on a folded and denuded surface of older beds. Were, however, the Carboniferous and Permian strata complete, it would be more correct to say that the movements commenced in late Carboniferous times and continued into the Permian.

SOME GENERAL REMARKS ON SYSTEMS OF FOLDING.

It has already been noted that folds connected with the Siluro-Devonian movements have a marked S.W.—N.E. or "Caledonian" trend. In the same way the late Carboniferous folds and faults generally followed a certain direction—or more correctly in this case one of several directions. These folds and faults are often classified according to their trend or direction, and the different groups are given special names. Such artificial groups are often referred to as if they were the result of distinct and separate series of movements. Great confusion has arisen owing to some authors restricting

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1 The hybrid word "Carbo-Permian" is comparable with the other terms "Siluro-Devonian" and "Cretaceo-Tertiary" used in this book. It is not intended to replace "Permo-Carboniferous," which has long been used to designate a group of rocks in the Southern Hemisphere which were deposited during the Carboniferous and Permian Periods, but are not readily separable.

these special names to movements of a definite date, whilst others apply them to any movements or the result of movements having the same general direction. Thus for some a " Caledonian " fold is a Siluro-Devonian fold running S.W.—N.E., whilst for others it is any fold having a trend approximately S.W.—N.E. If initiated at a later date than the main Caledonian folding it may further be distinguished as a " posthumous " Caledonian fold.

Speaking generally, one may say:

1. That the dominant direction of the folds and faults of any one period depends on the presence of resistant earth-blocks and the direction of the pressure and hence varies from place to place.

2. That if the varied directions of the folds of one period or in one area are distinguished by names it is unwise that a definite time value be associated with any one name. Thus the expression " Caledonian folding " has a much wider meaning than " the Siluro-Devonian folding."

3. That roughly the following is true of England :—

Pre-Cambrian Folds are mainly Charnian (N.W.—S.E.) in trend.

Siluro-Devonian Folds are mainly Caledonian (S.W.—N.E.) in trend.

Carbo-Permian Folds are mainly Armorican or Hercynian (W.—E.) in trend, or follow earlier lines of movement.

Tertiary (Alpine) Folds are mainly W.—E. in trend, and are often superimposed on Armorican Folds.

4. That a classification by direction is artificial, and it must not be inferred that the movements are not connected. Some of the Carbo-Permian folds run W.—E., others N.—S., the difference being due simply to the presence of stable earth-blocks which obstructed the earth-waves.

5. That movements at any period tend to take place along previously defined lines of weakness. Thus a large percentage (80 per cent.) of British earthquakes at the present day are associated with lines of folding or faulting which were initiated in early Palæozoic times. Similarly renewed movement frequently takes place along faults whose main throw is earlier.

6. That no great movements commenced or died down suddenly, but were preceded by smaller movements often growing *in crescendo* till the great storm broke and then died away gradually. This is exemplified by the minor folding of early Palæozoic time, which, in the main, has a " Caledonian " trend, and by the Carbo-Permian folding, which is heralded by the minor folding found throughout the Carboniferous

THE CARBO-PERMIAN OR LATE CARBONIFEROUS FOLDING IN THE BRITISH ISLES.

The numerous faults and folds shown on the map (page 175) may be grouped according to direction.

1. West—East Folds forming part of the great "Armorican" (Armorica, the ancient name of Brittany) or "Hercynian" (the Harz Mountains) folding of the Continent of Europe. They affect chiefly the South of England, and are there associated with the intrusion of the great granite masses of Devon and Cornwall.

2. The "Malvernian" Folds—north and south folds found chiefly in the West of England, and which may be due to the "swinging round" of Armorican folds against the stable block of Wales.

3. South-west to north-east folds (called Lancastrian folds in Lancashire, etc.), along the line of the older Caledonian folding. These are most evident in the north-west—in regions already affected by Caledonian movements (North and Central Wales, Anglesey, Lancashire, etc.).

4. North-west to south-east or "Charnian" folds—*i.e.*, renewed movement along Charnian lines. These are particularly conspicuous in the Midlands and North of England (Charnwood Forest, Nuneaton, Lickey Hills, etc.).

5. The so-called "Pennine" folding, with an apparent north to south alignment, seems to be largely, if not entirely, due to the interference of small echeloned folds of Caledonian and Charnian trends.

As far as possible the most important folds and faults are indicated on the annexed map (*Fig.* 41), which should be carefully studied and the relation between the regions of folding and the physiography of the Permian land (map, *Fig.* 42) noted. For the most part the Permian basins occupied synclinal hollows (as in Cornwall and Devon), or faulted regions (Vale of Eden). In some cases important folds like the Howgill Anticline were planed down before the Permian rocks were laid down across them.

FIG 40a. The geography of Coal Measure times (simplified).

FIG. 40b. The effect of subsequent earth-movements in separating the British Coal Measures into a number of basins.

(Reproduced from Stamp and Beaver's "The British Isles," by permission of Longmans, Green and Co., Ltd.)

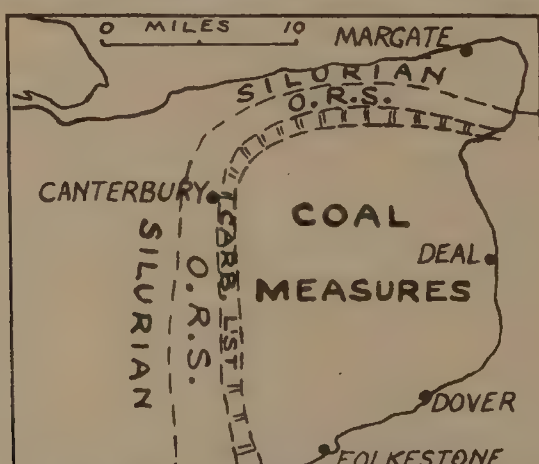

FIG. 40c. Sketch-map of the Palæozoic floor in East Kent.

FIG. 41. Map showing the principal Carbo-Permian folds and faults in England. (*L.D.S.*)

Compare the map given by Dr. R. H. Rastall, *Geol. Mag.*, vol. lxii., 1925, p. 214.

Fig. 42. The Geography of the Permian Period. (*L.D.S.*).

THE PERMIAN IGNEOUS ROCKS.

1. Scotland.

a. The volcanic group of Mauchline may be regarded as a resuscitation of the Carboniferous volcanic activity, and is described with the rocks of the latter (see page 147). Many of the volcanic rocks of Fifeshire are probably of the same age, and other patches of volcanic rocks most likely of Permian age also occur.

b. There are some small alkaline intrusions of Permian age. Some cut the Mauchline lavas, and must be later (see page 186).

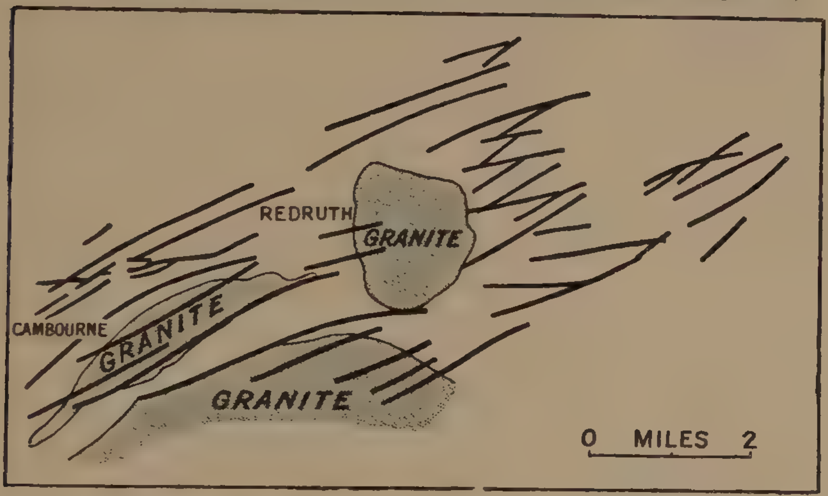

FIG. 42a. Sketch map showing the disposition of the tin and copper lodes in the Camborne-Redruth district, relative to the granite masses of Carbo-Permian age.

Reproduced from Stamp and Beaver's "The British Isles," by permission of Longmans, Green and Co., Ltd.

2. Cornwall and Devonshire.

a. The volcanic rocks in the immediate neighbourhood of Exeter are mostly decomposed lavas corresponding to the differentiated hypabyssal rocks, the Lamprophyres. Many are rich in potash, and have been described as basic trachytes (biotite-, augite- and olivine-trachytes), others as types nearer basalts.

b. The great granite masses of Devon and Cornwall break through, and have metamorphosed the Devonian and Carboniferous rocks, but fragments of the altered rocks are found in the Permian breccias, and the granites themselves may have been exposed. They are mostly two-mica granites, with large porphyritic crystals of orthoclase, and they often carry tourmaline. Wide-spread pneumatolytic action occurred at a late stage, and the bosses not only have extensive aureoles, but the important metalliferous lodes of Cornwall are associated with them. The large aureoles suggest that the granite masses have a dome-shaped

upper surface and, although spread over a wide area, the altered rocks are actually but a small distance from the surface of the granite below.

Associated with the granites, and but slightly later, are numerous dykes of quartz-porphyries or "elvans." They frequently contain tourmaline and pinite pseudomorphs after cordierite. They tend to have an E.N.E.—W.S.W. direction, and become more abundant to the west. Near the St. Austell and Bodmin Moor masses the direction is nearly E.—W. The tin and copper lodes also run E.N.E.—W.S.W. Silver and Lead ores occur as a later deposition in the same lodes, but are more abundant in another series of later lodes almost at right angles. Mica-lamprophyres also occur, far less abundantly and later than the quartz-porphyries. These tend to run N.—S. (*e.g.*, Falmouth and Truro districts).[1]

[1] For further details concerning the igneous and metamorphic rocks of Devon and Cornwall reference should be made to the Memoirs of the Geological Survey (especially Bodmin, Land's End and Falmouth Sheets). The formation of China-Clay from the granite should also be noted.

CHAPTER XI.

THE PERMIAN SYSTEM.

NAME (Murchison, 1841), from the ancient kingdom of Perm, in Russia, where rocks of this age are well developed. Also known as *Dyas* (Marcou), especially by the Germans, owing to the well-marked two-fold division of the German type of deposit into a lower Rothliegende and an upper Zechstein. In the British Isles, between the Carboniferous and the Rhætic or Jurassic, there is a group of beds predominantly red in colour, and hence formerly called the *New Red Sandstone*. These beds were afterwards separated into Permian below and Trias above, the former constituting the youngest division of the Palæozoic, the latter the oldest of the Mesozoic.

GEOGRAPHY OF THE PERIOD.

1. It has been noted that the end of the Carboniferous period was marked by extensive earth movements and by a general desiccation which commenced earlier in the north and gradually spread southwards. As a result of folding, some of the higher Carboniferous deposits were already being laid down in isolated basins (especially on the Continent, *e.g.*, France). In England red measures, indicating desert conditions, are contemporaneous with the higher coal-bearing strata further south (*e.g.*, in France).

2. The lowest Permian follows naturally in similar—often approximately the same—basins.

3. From late Carboniferous to well on in Permian times there was extensive uplift in North-Western Europe, whilst the sea covered Southern Europe and Asia and parts of Russia. As a natural result of the uplift isolated, or nearly isolated, arms of the sea were left in the north-west. Of these the most important was the great Germano-British Sea, stretching from Germany across the North Sea and covering the northern counties of England.

4. The continuance of earth-movements has given rise to numerous local unconformities in the Permian, and the igneous rocks of Exeter are possibly associated with such late movements.

CLASSIFICATION OF THE PERMIAN.

The type of truly *marine* Permian is not to be found in Northern Europe. It is perhaps best known in the Salt Range of Northern India, where an uninterrupted marine succession from the Carboniferous to the Trias is exhibited. The so-called "marine" Permian of North-Western Europe was laid down in a basin which may be compared with the Caspian or Red Sea of the present day—somewhat abnormal beds with an impoverished marine fauna.

The German type (including the British) of Permian may be divided into :—

		German Representatives.
3.	Thuringian.	Zechstein or Magnesian Limestone (with overlying marls), the Kupferschiefer (marl slate) at the base.
2.	Saxonian.	Upper Rothliegende.
1.	Autunian.	Lower Rothliegende (of German Survey).

PERMIAN IN THE BRITISH ISLES.

The folding movements in late Carboniferous times resulted in the formation of several basins, of which the principal are :—

1. Southern Basin—parts of Cornwall, Devonshire and Somerset.
2. Midland Basin—Southern Midlands.
3. Mauchline Area—Southern Scotland (Ayrshire).
4. Northern Scotland.

These four areas (with the possible exception of No. 3) may be regarded as freshwater or desert basins. There is also

5. The Pennine Area—forming an arm of the Germano-British Sea. The deposits of this basin of deposition occur on both sides of the Pennine uplift, but the deposits on the two sides present a considerable contrast. The eastern and

western regions were probably only connected by straits across the Pennines, or towards the latter part of the Permian period. The Midland Basin, already mentioned, was most probably connected with the western region, and an arm of the latter may have formed the Mauchline area.

These several basins of deposition were separated by ranges of mountains which assume a special importance in connexion with the source of material of the Permian deposits. The following may be postulated with certainty (see map, *Fig.* 42).

1. THE CORNUBIAN HIGHLANDS, occupying the greater part of Cornwall and adjoining regions. The great granite masses seen at the present day represent the denuded core of these mountains. It is noticeable that a long tongue of Permian still exists in the centre of the Devon synclinorium.
2. THE ARMORICAN FOLD-MOUNTAINS OF SOUTH WALES and the Mendip area, separating the Southern from the Midland Basins. It is probable, however, that a connexion was established between these two basins towards the end of Permian times.
3. THE WELSH MASSIF, bounded on the east by the Malvern Hills and the faults of the Vale of Clwyd.
4. THE MERCIAN HIGHLANDS, a ridge of old rocks occupying practically the same position as the Pre - Carboniferous ridge already described (page 134), and bounding the Midland Basin on the south. The mountain ranges, which together formed the ridge, actually cross it, and stumps remain as the hills of the Wrekin, Lickey, Nuneaton and Charnwood Forest.
5. THE PENNINE ARCH, probably forming a low discontinuous divide. Geologically the southern part is not a continuation of the northern part, which runs along the north-eastern frontier of the Lake District.

6. The Lake District, which is practically a horst, being surrounded by Carbo-Permian faults and folds (see map, page 176), one set of which has a Caledonian trend.
7. The Southern Uplands.
8. The Scottish Highlands.

In a few cases Coal Measures pass up conformably into Permian rocks (? as in Mauchline), but in the

Fig. 43. Map of Part of the Southern Permian Basin. Solid Black = Existing areas of Permian rocks, showing underground extension to the east. The deposits rest unconformably on Carboniferous in the centre, on Devonian (shown by horizontal ruling) to north and to south. Granite bosses (Carbo-Permian age) are shown by crosses. (*L.D.S.*)

majority of cases considerable denudation of Carboniferous rocks preceded the deposition of Permian strata. This is well seen in the case of the eastern Pennine area (Germano-British Sea), where the base of the Permian

transgresses from Coal Measures in the valley of the Tees on to Carboniferous Limestone, and then back on to Coal Measures in Nottinghamshire. These unconformities are indicated on the map, *Fig.* 42. In the case of "Permian" rocks resting conformably on Carboniferous it is often doubtful whether the beds should not themselves be classed as Upper Carboniferous (Scotland and Shropshire).

1. Southern Basin.

This occupies a tract between Dartmoor, Exmoor and the Mendip Hills, with an extension westwards along the Armorican fold valley (Crediton Valléy). The relationship of the beds may be seen from the accompanying diagrammatic section (*Fig.* 44) from the Cornubian Mountains in the south-west towards the north-east.

FIG. 44. Diagrammatic Section across part of the Southern Basin of Permian Times from the Cornubian Highlands towards the centre of the basin. (*L.D.S.*)

1. The **Watcombe Clays** are local—occurring especially round Torquay and again to the north by Teignmouth—and occupy hollows in the floor of the desert basin, being derived, probably, from the disintegration of Devonian Slates.

2. The **Breccias** and **Conglomerates** thicken to the west, and are banked up against the Cornubian mountains, from which they were derived. The matrix of finer material includes numerous very well rounded "millet-seed" desert sand-grains; this is far more the case than with the later Trias of the same area. The whole of the deposits in the basin are closely comparable with those forming in some of the existing desert basins in Persia. There are extensive screes of angular blocks—the angularity of which may be attributed to frost or sun action—mixed with fragments rounded during torrential

rains. The upper breccias (2b) differ from the lower (2a) in the presence of numerous fragments of igneous rock of types not now seen *in situ* in Devon or Cornwall.

3. The **Conglomerates** and **Sandstones** — up to 2,000 feet thick near Exmouth—are of the nature of outwash fans, such as are usually found associated with screes of angular material in present-day desert basins. Some of the material may have a more northerly source. In both the breccias and conglomerates bands of marl with sun-cracks and ripple-marks point to the existence of temporary lakes or pools during the wet seasons.

4. The **Marls** were laid down under more even conditions, when the surrounding highlands had been greatly reduced by denudation. They may be largely Triassic in age.

Contemporary igneous rocks at Exeter are also shown in the section. The Southern (or, as it is often called, the South-Western) Basin extended westwards along the English Channel and blocks of breccia have been dredged up nearly as far west as the Lizard. In Brittany there was a similar but probably separate basin. The abundant detrital staurolite[1] of the Permian sediments must have come from some now buried land in the south-west—it becomes more abundant in that direction, and does not occur at all commonly in the rocks now seen in Cornwall. The other detrital minerals could all have come from rocks now exposed in Devon and Cornwall. The Southern Basin was bounded on the north-east by the Mendip Hills, but the eastern limit is uncertain, as the rocks pass under Triassic sediments.

2. Midland Basin.

This second area was bounded on the south by a range of uplands known as the Mercian Highlands, stretching from the Malverns to Charnwood. Whilst the whole range runs therefore from south-west to north-east, the individual ranges which compose it have a Charnian trend, that is to say from north-north-west to south-south-east (Charnwood Forest, Nuneaton, Lickey Hills, etc.). The deposits are quite comparable in general character with those of Devonshire. The full succession is :—

c. Enville Marls.
b. Trappoid Breccia.
a. Conglomerate Group.

The lower coarser beds are banked up against the Mercian Highlands, and naturally thicken in that direction. The

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[1] H. H. Thomas, *Quart. Jour. Geol. Soc.*, vol. lxv. (1909).

Enville District (of South-Eastern Shropshire) may be taken as typical of the Midland Basin.

a. **Conglomerate Group** consists of fairly well rounded pebbles and blocks — about half of Silurian limestones and grits, etc., and about half of dolomitized Carboniferous Limestone. The former (including Woolhope and Wenlock Limestone) point to a southerly origin, and the latter are of the type found in South Wales (Forest of Dean), and not of that seen in the Wrekin area. Moreover, the massive conglomerate —75 feet thick—of the west-south-west splits up to north and east, and passes into calcareous sandstone.

b. **Trappoid Breccia** is composed largely of angular blocks of rhyolite, felspathic tuffs, etc., of Pre-Cambrian types, and similar to those found in the ridges of Nuneaton, Charnwood, etc. Blocks of Llandovery Sandstone and Woolhope Limestone also occur. The Breccia extends to the south as far as Great Malvern (Haffield Breccia). The deposit is of the nature of a scree from the Mercian Highlands. Some scratches on the blocks—due doubtless to the angular masses having rubbed one against the other—were formerly thought to indicate a glacial origin.

c. **Enville Marls** are, conversely, thicker to the north. They are non-calcareous.

The details of the Midland Permian Beds were worked out by Mr. W. Wickham King.[1] He considered the underlying red marls or Keele Beds (which follow conformably the productive Coal Measures) as "Lower Permian." It is just possible that the Conglomerate Group are highest Carboniferous, but in that case the constituent pebbles show that Carboniferous rocks had already been ridged up, denuded and older rocks exposed; that is, the conglomerate is at least younger than a great part of the Carbo-Permian folding.

The difference between the conglomerates and the succeeding breccias may be accounted for by supposing the former to be torrential deposits brought a short distance from the south, whereas the latter are scree material of more local origin (from the Mercian Highlands). The Breccias contain fragments of older rocks than do the Conglomerates, indicating that older rocks had been exposed by denudation, and probably also that renewed movements had taken place along old lines. From existing occurrences in Persia it is known that torrential deposits may be quite well rounded, even if they have travelled but a short distance. The Permian further east in Leicestershire is very similar. There is a lower breccia banked up against the Pre-Cambrian of Charnwood, Nuneaton and the buried ridge under Market Bosworth (the materials have been mainly derived from these ridges), succeeded by marls.

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[1] W. W. King, *Quart. Jour. Geol. Soc.*, vol. lv. (1899), p. 97.

3. Scotland, Mauchline Area.

In the Mauchline district of Ayrshire, resting conformably in a saucer-shaped hollow of upper Carboniferous rocks, is a series of lava flows, followed by tuffs, and then by a considerable thickness of red sandstone, the whole possibly Permian. A short distance from the outcrop of the lavas is a volcanic neck, from which they were probably poured forth.

Patches of red beds, probably of Permian age, also occur in Dumfriesshire (see below, page 190).

4. Northern Scotland, Moray and Elgin.

A series of red sandstones, apparently deposited in a wind-swept desert basin, occurs along the coasts of Moray Firth. The beds have been classed as Permian from the occurrence in them of footprints (*Gordonia*, *Geikia* and *Elginia*) very similar to some found in undoubted Permian at Mansfield and in Lancashire.

5. The Pennine Area (part of the Germano-British Sea).

The deposits fall naturally into two types, an eastern and a western, on the two sides of the Pennine Uplift respectively. The arm of the sea opened out to the north-east (*e.g.*, Durham), where the beds are predominantly marine (Magnesian Limestone). The deposits become more arenaceous or marly to the south (Nottinghamshire). The sea stretched across the partly raised Pennines at least in certain areas, so that one finds shallow water (arenaceous) deposits to the west of the Pennines, with but thin bands of magnesian limestone in the upper part. At the same time there seems to have been a return current from west to east bringing sand into the Magnesian Limestone sea of the Mansfield District.

a. Eastern Type.

The various beds present may best be shown by means of a diagrammatic section from south to north (*Fig.* 45). The general character of the Permian and Trias is readily apparent, but it will be noticed that there is a difference of opinion as to the age of, and the relation

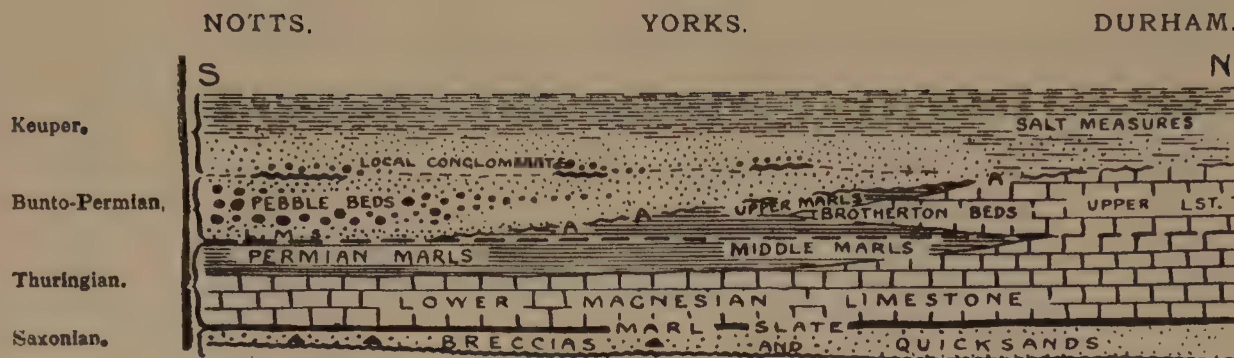

FIG. 45. Diagrammatic Section of the Permian and Triassic Deposits of the Eastern side of the Pennines (*L.D S*)

ship between, the beds in different areas. Sherlock[1] has adduced evidence for considering the upper part of the "Permian" Magnesian Limestone of Durham as the lateral equivalent of the Bunter Sands and Pebble-Beds of Nottinghamshire. A considerable number of geologists adhere to the older point of view, and believe there is an unconformity (as indicated on the diagram, ***Fig.*** 45 by A-A-A) between the Trias and Permian.

DURHAM. The basal yellow sands range from 0 to 150 feet in thickness. The Marl Slate, though less than 10 feet thick, is an important datum line, as it yields fish remains (*Palæoniscus*) and other fossils which serve to identify it with the Kupferschiefer of Germany. The Magnesian Limestone is divisible into three portions; the lower is a compact brown limestone (40-200 feet), and yields a few fossils, including *Productus horridus*; the middle is a cellular limestone (150-300 feet) and is the main fossiliferous horizon. It yields a fauna of stunted brachiopods (the spiny *Productus horridus*, *Camarophoria schlotheimi*, *Spirifer alatus*) and lamellibranchs (*Bakewellia* and *Schizodus*). The upper portion has a bed of flexible sandstone with fish-remains at the base, whilst the overlying limestone has yellow concretions in the lower part, but becomes fairly well bedded in the upper part. Conditions during the formation of the Upper Limestone had become still more adverse to life, and only a few stunted lamellibranchs remain, together with the abundant bryozoan *Fenestella*. The overlying gypseous marls have a band of red sandstone at the base in the south-east of the county.

YORKSHIRE. The Upper Limestone is here represented by the Brotherton Beds. Triassic affinities in the fauna seem to be indicated by such fossils as the plant *Voltzia*. The Lower Magnesian Limestone yields a characteristic fauna in certain localities, including brachiopods (*Productus horridus*, *Camarophoria schlotheimi*, *Dielasma elongata* and *Spirifer alatus*), lamellibranchs (*Schizodus*, *Bakewellia* and *Monotis*), bryozoans (*Fenestella retiformis*), the plant *Walchia* and the fish *Palæoniscus*.

NOTTINGHAMSHIRE. The lowest beds are breccias and sands, and are succeeded by the Marl Slate—again fossiliferous. In some localities the overlying Magnesian Limestone yields the same characteristic fauna as in Yorkshire. It is noticeable that the Permian becomes thicker and more calcareous when traced eastwards under the Trias (*e.g.*, towards Newark). An interesting phenomenon is to be observed in the Magnesian Limestone of Mansfield, where a band of false-bedded dolomitic sandstone—the famous Mansfield Building Stone—occurs. It is found at a low level in the limestone to the west, but gradually rises to higher and

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[1] R. L. Sherlock, *Quart. Jour. Geol. Soc.*, vol. lxvii. (1911). See also his later studies, *Proc. Geol. Assoc.*, vol. xxxvii. (1926), pp. 1-72; *ibid.*, xxxix. (1928), pp. 49-95.

higher horizons eastwards, as if a current coming from the west had poured in arenaceous material during the formation of the Magnesian Limestone, and had gradually pushed the sediment further eastwards as time went on.

b. Western Type.

Extends from North-Eastern Cheshire, Lancashire and the Eden Valley of Cumberland westwards to the Isle of Man and across the Northern part of Ireland.

(i.) The Vale of Eden. The Permian is bounded on the east by the Carbo-Permian fault-scarp of the Pennine Fault. Naturally the lowest deposits are breccias and conglomerates—the latter are dolomitized and calcareous—known as Brockram, originally having been part of screes from the uplifted Pennine Ridge.[1] The beds rest unconformably on Carboniferous Limestone and Millstone Grit. These basal beds are succeeded by bright red sandstones (Penrith Sandstone), with some breccia (the Upper Brockram) in the higher part. The sandstones are remarkable for the growth of secondary quartz, often showing good crystal form, around the rounded iron-stained sand grains. The original grains show the grading and polishing characteristic of æolian deposits. Reptilian tracks occur. The Sandstone is succeeded by the Hilton Plant-beds, with a Permian flora, and then, as if the eastern sea had flowed across the low Pennine ridge, by a thin representative of the Magnesian Limestone. This is succeeded by gypseous marls, often with a basal conglomerate.

At Ingleton, at the foot of the Craven fault-block, a brockram occurs with fragments of Millstone Grit, Carboniferous Limestone and older rocks.

At Barrowmouth (west of the Lake District) Magnesian Limestone, with a basal breccia, rests unconformably on Carboniferous Limestone.

It should be noted that round the Lake District there is evidence in the different material which makes up the *Upper* Brockram (including fragments of basal Carboniferous and Ordovician) of local movement along the neighbouring faults during Permian time. Moreover, the Gypseous Marls sometimes rest uncomformably on Penrith Sandstone.

(ii.) Lancashire. Fringing the coalfield are Permian Rocks, with a thin basal breccia, followed by red or variegated sandstone (Collyhurst Sandstone), and then by marls and limestones, with marine fossils (*Schizodus*, *Bakewellia*, etc.). Towards the south an "Upper Breccia"—sometimes unconformable on Collyhurst Sandstone—underlies the marls.

In Cheshire fossiliferous marls with nodules of septarian nature represent the Magnesian Limestone.

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[1] See the interesting account of the conditions of formation compared with present day conditions in Central Asia, given by B. Smith, *Geol. Mag.*, vol. lxi., 1924, pp. 301-305.

(iii.) Isle of Man. In borings in the north of the island the Trias (St. Bees Sandstone) is found to pass down into red marls, and then into coarse sandstones, with partings of marl and with a fine "brockram" at the base. Part of these beds at least must represent the Permian.

(iv.) Ireland. The Eastern Sea stretched across—probably at a late stage only—into Northern Ireland and Magnesian Limestone with *Productus horridus*, *Bakewellia* and *Schizodus schlotheimi* occurs at Hollywood in County Down: unfossiliferous Magnesian limestones and shales are also found in the Lagan Valley. Underlying the Triassic sandstone of Armagh are boulder-beds like the brockram of the Eden Valley. The materials show that the Carboniferous Limestone was exposed to denudation in the south.

(v.) Scotland. The red sandstones—sometimes with reptilian footprints of Permian type—which occupy deep valleys eroded in the Southern Upland complex, especially in Dumfriesshire, have already been mentioned. Some red rocks in the Isle of Arran and elsewhere along the West Coast of Scotland have been regarded as Permian.

ECONOMIC GEOLOGY OF THE PERMIAN.

1. Building Stones. Several of importance.

a. Permian Breccia is occasionally used in Devonshire.

b. Penrith Sandstone is important—used on the old L.N.W.R. (L.M.S.) for bridges.

c. Magnesian Sandstone of Mansfield, Nottinghamshire. Both the red and white varieties of Mansfield Stone are much used (*e.g.*, St. Pancras Station and New Law Courts, London).

d. Magnesian Limestone is quarried in numerous places in the North and Midlands. Huddlestone Stone (Yorks) was used for Charing Cross Station; stone from Bolsover Moor (Derbyshire) for the Houses of Parliament. The bad way in which the latter have weathered is partly due to indiscrimination in quarrying, partly to the supplementary use of other stones (Arnston Moor, Yorks) and partly to the peculiar conditions of a London atmosphere, certain gases tending to attack magnesian limestones rather than pure limestones.

2. Clays. The Permian marls are of little use except for red building bricks, which, together with red roofing tiles and flower pots are made near Nottingham.

3. Sands.

a. Glass sands—no Permian sands are suitable.

b. Moulding sand. Very little importance.

4. Refractory Materials. As a rule the Magnesian Limestone is not compact enough, but it is quarried to a small extent in Durham.

5. Scenery. The marls form cultivated and pastoral country, the other beds are less cultivated. The Magnesian Limestone fre-

quently affords some picturesque scarp scenery, as at Knaresborough, Yorkshire.

PERMIAN IN GERMANY.

It is instructive to compare the development of the Permian in Germany since there one is approaching the other side of the Germano-British Sea, towards the main ocean of the south. Consequently one finds a richer fauna, but still not one which can be regarded as a typical marine Permian fauna. The succession is

Thuringian	Marls.	
	Magnesian Limestone (Zechstein).	
	Kupferschiefer (=Marl-State of England).	
	Weissliegende.	
Saxonian	Upper Rothliegende.	
Autunian	Lower Rothliegende	Lebach Group.
		Cusel Group.

The beds are well developed in the Sarre Valley, Saxony and Thuringia.

Autunian. The flora is typically Stephanian, with the addition of some Permian Species (*Walchia piniformis*, *Calamites gigas* and *Callipteris conferta*). Coals occur in the Upper Cusel.

Saxonian. Some thin coals still occur. *Walchia* and *Callipteris* are thoroughly typical.

Thuringian. The lowest bed is a conglomerate; the Kupferschiefer is so called from its (former) importance as a source of copper ore (especially at Manfeld), it yields *Palæoniscus* and the plant *Ullmannia*. The Zechstein contains *Productus horridus* and *Fenestella*. The famous Stassfurt and other salt deposits occur in the Upper Thuringian.

PERMIAN IN FRANCE (the Sarre Valley is considered with Germany).

Autunian, resting conformably on Stephanian, occurs in the Autun Basin of the Central Plateau. It yields *Walchia piniformis* and *Callipteris conferta*, and shows the truth of the statement that the desiccation of early Permian times came on earlier in the north (pre-Stephanian in England) than further south (France).

In the Alps plant-bearing sandstones in the north pass southwards into more truly marine beds. The latter are characterized by the abundance of *Fusulina*, the dying out of Palæozoic Goniatites, Orthoceratids, and by the appearance of Mesozoic types of Ammonites and Gastropods.

LIFE OF THE PERIOD.

Truly marine Permian is only found in a few areas—mostly in the tropical or subtropical regions; the fauna and flora of the Permian in North-Western Europe are impoverished remnants of the Carboniferous fauna and flora. In general terms the Permian is remarkable for the appearance of reptiles; the disappearance of the goniatites and the appearance of the ammonites—or perhaps more correctly one should say that the Ammonoidea develop far

more complex suture lines. The last of the Orthoceratidæ and the very last trilobite (in North America) occur in Permian rocks.

a. Plants. The flora is that of the Upper Carboniferous (which gradually dies out during the period) with the addition of *Walchia*, *Callipteris*, etc.

b. Vertebrata. There are various characteristic fish (*Palæoniscus*). Reptiles appear.

c. Arthropoda. Not important, owing largely to condition of deposition of the beds.

d. Mollusca. Among Lamellibranchs the Schizodonts are most important; *Bakewellia* is the forerunner of the Mesozoic *Pernidæ*.

e. Brachiopoda. Many of the Carboniferous genera are represented, but in much reduced numbers.

f. Polyzoa. *Fenestella* is an important rock-forming organism in the Magnesian Limestone.

g. Echinodermata. The last Blastoid occurs in the Permian. The ancestors of the great Cidaroid stock arose in this period.

The sparsely fossiliferous Permian and Triassic rocks of Britain give very little idea of the contemporary life, and one is accustomed to think of a marked break between the later Palæozoic faunas of England (Carboniferous) and the earlier Mesozoic faunas (Jurassic). As will be seen from the above account the fauna of Permian and likewise that of the Trias are in reality transitional.

CHAPTER XII.

THE TRIASSIC SYSTEM OR TRIAS.

NAME. The name "Trias" was given to this group of rocks by Von Alberti in 1834 from the three-fold division in Germany. The name is a bad one, it is only of local significance, and is not even applicable in England. Moreover, the succession on which it is based is not a typical marine one. The Trias forms the upper part of the New Red Sandstone of older English writers, and, owing to the frequent difficulty of separating Permian and Triassic rocks, that name is still retained for the two by some authors.

GEOGRAPHY OF THE PERIOD—GENERAL.

In Germany the Trias is divisible into

$$\begin{cases}\text{Keuper,}\\ \text{Muschelkalk (marine),}\\ \text{Bunter.}\end{cases}$$

In England into

$$\begin{cases}\text{Keuper,}\\ \text{Bunter.}\end{cases}$$

In England, however, if there is any unconformity between the Keuper and Bunter it is very slight, and the Muschelkalk must be regarded as a marine intercalation increasing in importance as one approaches the open sea of the Alpine Region (*Fig.* 46).

Speaking generally, one has a continuation of the Permian conditions in Triassic times. The mountains which surrounded the Permian desert-basins had become more rounded and lower, hence one finds conglomerates brought down by torrents rather than angular blocks of scree materials. On the whole, too, deposits become finer and more widespread as one goes upwards in the Triassic succession, showing that, as the surrounding mountains were worn down, the desert-basins extended their limits and partly covered them The lower the sub-

division the more limited its extent. In England the Triassic areas of deposition may be described as deserts with sand-dunes, affected by periodic rushes of water in otherwise dry valleys, and characterized by the formation of shallow stretches of water, fresh or more often saline, which frequently dried up.

GEOGRAPHY OF ENGLAND—Bunter Times.

There were two main areas of deposition. One was in the south-west—corresponding to the South-Western Permian Lake—probably a lake surrounded by areas of blowing sands and entered by rivers bringing great masses of pebbles in flood seasons. The other was in the North of England—a great arm of the Germano-British

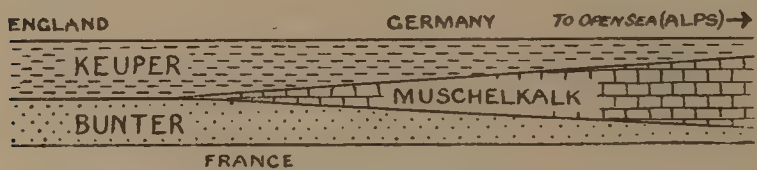

FIG. 46. Diagram showing the twofold and threefold divisions of the Trias. (*L.D.S.*)

gulf stretching across to Northern Ireland and surrounding the Pennines—a low island. The truly marine waters of the gulf had, however, retreated right into Germany since Permian times, so that there is practically no trace of a marine fauna in England, but the presence of salt attests the salinity of the waters.

Keuper Times.

The Keuper deposits are much finer and more widespread. The two areas of deposition of Bunter times had joined up and become much more extensive (see map, *Fig.* 47). The regions were in great part shallow salt lakes with fringing beaches, and in part plains of blowing sands with pools in the wet seasons. The conditions are, on the whole, perhaps most comparable with those existing round the Great Salt Lake of Utah.

FIG. 47. Palægeographical Map of Triassic Times. Existing outcrops of Trias in black. (*L.D.S.*)

The coastlines in Ireland were later traced with greater accuracy by Reynolds (see p. 203).

GEOGRAPHY OF GERMANY.

Germany was largely covered by the Germano-British Gulf, open to the main ocean of Southern Europe. In the same way that the Zechstein or Magnesian Limestone is a specialized and impoverished type of marine Permian, so the Muschelkalk is a specialized and impoverished type of marine Trias.

TRIAS IN THE BRITISH ISLES.

1. South-Western Area (Devon and Somerset).

The accompanying map and diagrammatic section show the succession and distribution of the beds (*Figs.* 48-9).

The famous Pebble-Beds of Budleigh Salterton, which rest directly on Permian marls, were probably deposited by great seasonal rushes of water. Similar phenomena are observed at the present day on the borders of Afghanistan and Persia, where the Helmand River periodically brings down masses of *well-rolled* pebbles. Some of the pebbles of Budleigh Salterton may be matched in rocks of Devon and Cornwall, but the majority must have been derived from the Ordovician rocks of Normandy or Brittany. A small patch of Ordovician rocks also occurs in the extreme south of Cornwall (Lizard District). The Ordovician pebbles are fossiliferous, and, whilst many of the fossils are unknown elsewhere in Britain, they *all* occur in the "Grès de May" of Normandy (*Orthis budleighensis*, etc.).

Further north, between Burlescombe and Williton, a similar bed with numerous pebbles of Carboniferous Limestone, which must have come from the north, points to the existence of another river coming from that quarter.[1] A careful study of the heavy minerals in the sand associated with the Pebble-Beds confirms the evidence afforded by the pebbles themselves.[2]

As seen from the section the Pebble-Beds are covered by sands—in part they tail out to the north and are replaced by coarse sands—and then by Keuper deposits. The latter comprise great thicknesses of red marls with

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[1] E. C. Martin, *Geol. Mag.*, vol. xlvi. (1909), pp. 150-7.
[2] H. H. Thomas, *Quart. Journ. Geol. Soc.*, vol. lviii. (1902), pp. 620-632.

FIG. 48. Sketch Map of the South-Western Bunter Lake. Land areas are marked by vertical lines. (*L.D.S.*)

FIG. 49. Diagrammatic Section across the same. (*L.D.S.*)

strings of gypsum and pseudomorphs after rock-salt. Celestite is mined near Bristol. The coastal deposits of this Keuper Lake are well seen in parts of South Wales (near Barry); in the Mendips where they run up and fill in pre-Triassic valleys in the Carboniferous Limestone, and also round the Quantock Hills, which must have formed an island. These coastal deposits are naturally not always of the same age, and various horizons of the Keuper Marls pass laterally into them. Even the Tea-Green Marls at the top have their coastal representatives. They generally consist of a coarse conglomerate with large boulders of the underlying rocks or of rocks transported but a short distance. The conglomerate is known as the Dolomitic Conglomerate. When the underlying rock is Carboniferous Limestone the boulders are largely of that material, and the matrix of the conglomerate is often dolomitized, so that the name is not inappropriate. Elsewhere, as Mr. Whitaker once remarked, the name is no more appropriate than is plum-pudding for a pudding with raisins, though long usage justifies its retention.

The Keuper Marls are generally red, but pass upwards into a group of green marls — the "Tea Green Marls"—well seen at Aust Cliff on the Severn or along the Watchet Coast of Somerset.

The eastern margin of the Keuper Lake is uncertain, but the presence of coastal breccias probably of this age under the Jurassic and Cretaceous of East Kent may afford some indication. There they seem to be banked up against land to the north and east. To the north the Keuper region of the south-west joins up with that now to be described.

2. Midland and Northern Area.

The full succession is :—

Keuper { Keuper Marls.
Keuper Waterstones with Basement Bed.

Bunter { Upper Mottled Sandstone.
Pebble Beds.
Lower Mottled Sandstone.

The general arrangement of the beds is illustrated in the section *Fig.* 50. It should be noted that the beds are

banked up against the remnants of the old Mercian Highlands. The following remarks apply especially to the western side of the Pennines.

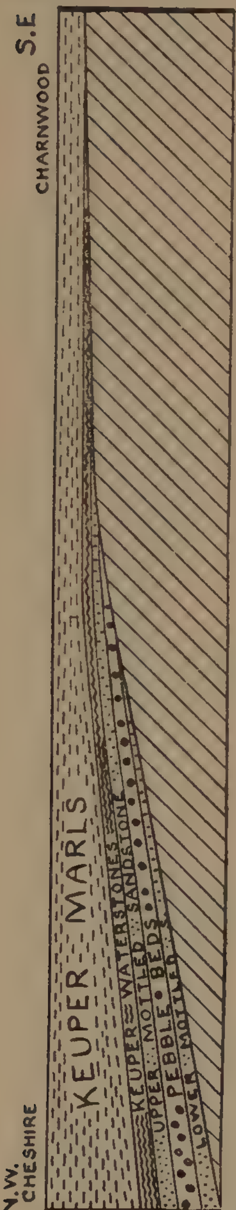

FIG. 50. Diagrammatic Section across the Trias of the Midlands. (Redrawn with modifications from Lake and Rastall's "Text Book of Geology," by permission of the authors and of the publishers, Messrs. Edward Arnold & Co.)

The LOWER MOTTLED SANDSTONE generally rests unconformably on Permian or Coal Measures—as in Cheshire and Shropshire. There is usually a basal breccia, otherwise pebbles or angular fragments are absent. The sands are current-bedded, and in some beds millet seed grains occur, almost exclusively. This division thins to the north of Cheshire and in South Lancashire. The beds were probably laid down on a desert plain (*i.e.*, æolian), which may have extended as far to the north-west as Ireland. Further north, on either side of the Pennine Range—namely, in the Carlisle and North Yorkshire districts — were two regions, probably lakes, in which red clays with layers of rock salt were being deposited.

The PEBBLE BEDS occasionally have a basal breccia, but consist for the most part of well-rounded liver-coloured quartzites. They are well developed in South Staffordshire, and overlap to the east (that is, on to the southern extension of the Pennine ridge, showing that it was at least partially unlifted before this period) and form

a thick mass resting on Coal Measures at Cannock Chase (300-400 feet thick). They are thicker still near Liverpool and St. Helens (600 feet with 400 feet of coarse sands above), and again overlap to the north-east. The nature and origin of the pebbles is very interesting. In Staffordshire and Shropshire they comprise :—

Quartzites	60—70 per cent.
Vein quartz	10—20
Grits	10—15
Igneous "felstones," etc.	4— 6
Carboniferous rocks ...	3— 6
Tourmaline Grits	1— 2

The quartzites can be matched in the Old Red Sandstone and Lower Carboniferous conglomerates of Southern Scotland, and also among the quartzites of the North and West of Scotland, but not among the rocks of the Lickey or Nuneaton ridges. But a few have been found containing *Orthis budleighensis*. Are these exceptional, or would a southerly source be found for the majority of the pebbles were the rocks forming the old Mercian Highlands better known? The grits are quartz-felspar grits comparable with the Torridonian of Scotland or the Grès felspathique of Northern France. The "felstones" cannot be matched in Wales, but in the West of Scotland similar rocks occur as pebbles. The Carboniferous Rocks are mainly local. As the evidence stands at present it points to a river coming from the north-west, and bringing these masses of pebbles during seasonal or spasmodic floods.[1] The associated sand grains are mostly angular. The River Po at Piacenza has been instanced as an example of a river which is able to deposit a great spread of coarse gravel after having travelled over a hundred miles of plain.

The Upper Mottled Sandstone is very like the Lower. Its absence near Nottingham may indicate small intra-Triassic movements.

The Keuper Basement Bed (100—250 feet) generally ravines the Bunter, but there is not a big unconformity. It is a coarse sandstone, markedly false-bedded. Like the underlying beds, it thins to the south-east, and is absent in Warwickshire.

The Keuper Waterstones are brownish sandstones, sometimes very micaceous, false- or evenly-bedded. The upper beds have yielded an interesting series of fossils at

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[1] This is corroborated by the heavy minerals. Abundant staurolite, sillimanite, kyanite and microcline in the Midlands all point to a northerly or north-westerly origin. See T. H. Burton, *Quart. Jour. Geol. Soc.*, vol. lxxiii. (1917), pp. 328-337.

Bromsgrove.[1] The fossils include the amphibian *Mastodonsaurus giganteus*, which is common in the Lettenkohle Group of Germany (*i.e.*, post-Muschelkalk), whereas the accompanying plants (*Schizoneura paradoxa, Yuccites vogesiacus* and *Voltzia*) are those characteristic of the Upper Bunter of the Vosges (*i.e.*, pre-Muschelkalk). This strengthens the argument that the Muschelkalk is to be regarded as a *facies* rather than as a time-horizon, which is absent in England. Indeed, in Germany the "facies-fossils" of the Muschelkalk do reappear at a much higher horizon (at the top of the Lettenkohle Group). *Estheria minuta* is common at Bromsgrove, and suggests a comparison with dry districts of South Africa, where *Estheria* appears in myriads after rain in the "vleys" or wet-season pools. Numerous scorpions are also amongst the interesting fossils, whilst a doubtful "*Mytilus*" (? marine) may indicate a remote connexion with the Muschelkalk Sea of Germany. Bones usually occur with clay-galls as "osseous conglomerates," which are undoubtedly coastal deposits. It is interesting to see how the evidence as to conditions of formation of these waterstones has been summarized.

In favour of æolian origin :—

1. Absence of bedding—oblique or otherwise.
2. Sharp demarcation of marl beds, both above and below
3. Lenticular "lifts" simulating sand-dunes.

Against æolian origin :—

1. Many angular grains—only some of the larger ones are rounded.
2. Presence of *Estheria* and fish.
3. Well-preserved plants.

Conclusions : Between the land of Wales and the old Mercian land to the south-east there existed a gulf with a narrow connexion to Dorset ; a coastal area with sand-dunes bordered this brackish water gulf, and periodic rains gave rise to shallow pools in the wet season, around which a comparatively rich vegetation sprang up.

The Keuper Marls are very thick in Cheshire, but again thin out towards the old Mercian Highlands. The latter were, however, almost entirely covered at the end of Keuper times. Charnwood forms a buried hill range, and when the marl is removed from the Mount Sorrel

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[1] L. J. Wills, *Proc. Geol. Assoc.*, vol. xxi. (1910), pp. 249-331.

Granite the surface of the latter appears grooved and polished as if by the action of the Triassic desert winds. It has been suggested that the extremely "weathered" condition of the Pre-Cambrian Rhyolites of the Wrekin is due to their exposure to atmospheric agents practically since Permian times. The Wrekin probably formed an island even in the Keuper Lake, whose sediments wrap around its base on all sides. The Keuper Marls are a monotonous series of red or mottled green and red marls, with strings of gypsum and pseudomorphs after cubes of salt. Salt occurs in them in Cheshire. In Gloucestershire, Worcestershire and Warwickshire, about 110 to 215 feet below the top of the marls, there is a prominent sandstone—the Arden Sandstone — which has yielded fossils (*Hybodus, Acrodus,* the plants *Equisetites, Voltzia,* etc.).

In the highest parts of the marls is a variable thickness of "Tea-Green Marls," and in or just below these most of the important deposits of gypsum are found.

The foregoing remarks apply especially to the Midlands and the western side of the Pennines. Traced northwards along the EASTERN SIDE of the PENNINE RANGE (see diagram, page 187) one may note the importance of the Lower Mottled Sandstone as a moulding sand at Mansfield. The Pebble-Beds thicken to Selby and then die out, unless the Upper Magnesian Limestone of Durham is their lateral equivalent. The Upper Mottled Sandstone is absent, and the Basement Bed of the Keuper may be represented by a local deposit of white sand. Usually, however, the Keuper Waterstones seem to rest unconformably on underlying beds, and have a pebble-bed at the base. They consist of brown sandstone and red marls with suncracks, ripple-marks, etc., and pass up gradually into the Keuper Marl. The latter may include thin bands of whitish sandstone, and beds of gypsum become important in the upper part, as at Newark and to the south-east of Nottingham. In the highest part are the Tea-Green Marls, but the bulk of the Keuper Marls, as everywhere, is red or mottled. Various explanations of the mottling have been given; possibly the marls were originally slightly calcareous and the passage of chaly-

beate waters readily caused the replacement of Calcium and Magnesium by Iron. Later exposure resulted in the oxidation of the iron locally (giving red patches); where the protective covering of Rhætic is thick there the unoxidised Tea-Green Marls are thick also.

CUMBERLAND. Traced northward along the western side of the Pennines into Cumberland (Morecambe and the Valley of the Eden) one finds the Bunter represented by a pebbly sandstone up to 1,000 feet in thickness (St. Bees or Garstang Sandstone). The overlying Keuper comprises the Kirklington Sandstone below and Red Marl with gypsum above. The St. Bees Sandstone is seen also in the Isle of Man, and probably also in Arran.

IRELAND. In Ireland (valley of the Lagan, etc.) a soft red and yellow sandstone with shales (Bunter, 800 feet) is succeeded by brownish sandstone, salt-bearing or blue clays and red gypseous marls (Keuper, about 1,000 feet).[1]

SCOTLAND. Red Sandstone, of Triassic or Permian age, occurs as various small patches in Southern Scotland; red calcareous marls more certainly Triassic underlie the Jurassic along the western coast (Skye, Raasay, Mull, Ardnamurchan, etc.). A small Triassic Lake seems to have existed on the East Coast in the same position as the Permian Basin. The beds overlying the sandstone with supposed Permian reptiles, have an undeniably Triassic fauna.

THE TRIAS IN GERMANY.

The conditions were very similar to those prevalent in England, and both the English and German Trias belong to the "German Type." The German Trias was, however, laid down in a gulf opening out into the main ocean to the south (where the "Alpine Type" was being deposited), and is therefore more marine.

3. Keuper		Gypskeuper.
		Lettenkohle Group with coals and plant-bearing beds.
2 Muschelkalk	Upper	*Ceratites nodosus* Beds (very fossiliferous)
		Trochitenkalk with *Encrinus liliiformis*.
	Middle	Dolomites with gypseous and saline marls.
	Lower	Bedded grey limestone, ammonites appear.
1. Bunter		A varied series of beds with red sandstones predominating.

[1] For a reconstruction of the geography of the period see D. L. Reynolds, *Geol. Mag.*, vol. lxv., 1928, pp. 448-473.

As in England, the lower divisions are more restricted in lateral distribution than the higher beds. The chief interest centres on the Muschelkalk with its definitely marine but impoverished fauna. The well-known crinoid *Encrinus liliiformis* often makes up beds of considerable thickness. The Muschelkalk dies out westwards as one passes into France. There the Bunter is known as the "Grès bigarré" and the Keuper as the "Marnes irisees."

ALPINE TYPE OF TRIAS.

The deep-sea or Alpine Type of Trias is especially well developed in the beautiful Dolomite Mountains of the Tyrol. There are certain differences to be observed in the higher beds as developed in the north ("Juvavian Province") and in the south ("Mediterranean Province"). The latter province extended from Southern Tyrol through Italy into Bosnia, etc. Resting conformably on the Permian and with a lower limit which is often difficult to fix, is a series of sandy, saliferous shales—the Werfen Beds. These are usually correlated with the Bunter. The Muschelkalk is represented by limestones with *Ceratites binodosus* in the lower part and *C. trinodosus* in the upper. The separation into "Juvavian" and "Mediterranean" provinces becomes marked in the succeeding beds. The higher part of the Trias (*i.e.*, Keuper) is usually divided into Norian below and Carinthian above.

In the Mediterranean province the Norian comprises platy limestones and sandstones, with numerous coral reefs; the succeeding Carinthian consists of marly beds also with reefs—generally dolomitized.

In the Juvavian province marly beds mark the lower part of the Norian. They are followed by massive cephalopod limestones and marbles (Halstatt Marble), representing the upper part of the Norian and lower part of the Carinthian.

In the later Carinthian times the two provinces were no longer distinct, and dark bituminous shales and limestones with *Trachyceras* occur in both areas.

It is interesting to note that the two types of Trias are also found in America: the German type in the Rocky Mountains and elsewhere, the Alpine Type in California.

ECONOMIC GEOLOGY OF THE TRIAS.

1. Building Stones. The Bunter is used in South Lancashire; the St. Bees Sandstone of Cumberland was used in Windsor Castle. Sandstones of Keuper age (sometimes mottled) are quarried at numerous localities in Worcester, Cheshire and in Scotland. Stone from the Hollington Quarries (Stoke-on-Trent) was used in Hereford Cathedral.

2. Clays. In the Midlands (Nottinghamshire and Leicestershire) the Keuper marls are used for red bricks and in Somerset-

shire for red tiles. Owing to the presence of Gypsum the Keuper marl is notoriously treacherous. In baking the bricks the gypsum (hydrated sulphate of calcium) passes to the almost anhydrous form (Plaster-of-Paris), which, when exposed to damp, swells and bursts the brick.

3. Sands.

a. Glass Sands. Some sand, sufficiently good for bottle-glass, is obtained from the Bunter (Worksop) and from the Keuper Waterstones (Cheshire). A good glass sand should be of even grade, clean, with a high silica per centage, and with few heavy minerals.

b. Moulding Sands. A moulding sand must be refractory (*i.e.*, fluxes — Calcium salts including fluorspar, etc.—should be *absent*), and it must have a good bond to enable it to be built up into shaped moulds. Ferric oxide is especially good as a bond. The Bunter yields a world-famous moulding sand, and the annual consumption is enormous. All its characters are due to the desert conditions under which it has been formed — roundness of grain, red colour and efficient bond of iron oxide. Mansfield (Nottinghamshire) is an important centre. It is not sufficiently refractory for open-hearth steel furnaces.

4. Iron Ores. Rarely occur in payable quantities in the Trias, but where Triassic (or Permian) rocks rest on Carboniferous Limestone replacement of the limestone by iron salts from percolating waters have given rise to rich iron ores (as in South Wales and the Lake District). Thin sheets of ore sometimes occur along the Trias—Carboniferous Limestone junction. Some of the deposits may be due to primary deposition on the floor of the Triassic Lake or to contemporary replacement of the limestone.

5. Salt. Especially important in the Keuper marl of Cheshire and Worcestershire.

6. Gypsum. A little occurs in the Vale of Eden in the Bunter, but very important are the deposits in the upper 150 feet of the Keuper Marls, especially at Newark (Notts), but stretching also northwards to beyond Middlesbrough and southward to Gloucestershire. South Durham is the leading area of production of the anhydrous form, anhydrite. Gypsum has many uses.

a. Finer varieties (alabaster) for alabaster ornaments.

b. "Mineral white" is gypsum very finely ground (there are three grades), and is used for "filling" paper—*i.e.*, filling up the pores in paper; for finishing cotton and lace goods; for paint and for adulteration of various substances.

c. "Brewer's gypsum" is used for making non-gypseous waters permanently hard. A gypseous water (as obtained from wells in the Trias at Burton) is good for brewing.

d. Fertilizer (for hops in Kent and Sussex).

e. In the storage of manure—it preserves the ammonic content.

f. The manufacture of Plaster of Paris—which is gypsum with the water of crystallization largely driven off. This is performed in two ways: (i.) by baking lumps of gypsum and grinding; (ii.) by boiling—the gypsum becomes liquid by reason of its own water of crystallisation.

7. Celestite (used in pyrotechny and in the beet-sugar industry) was obtained from the Keuper Marl at Yate (Gloucestershire).

8. Water. Next to the chalk the Bunter is the most important water-bearing formation in England. It has a high water content when saturated, owing to the presence of millet seed grains, which do not pack tightly together. It is estimated that one-third of the rainfall falling on Bunter sandstones can be recovered. The Keuper Waterstones occasionally yield an abundant supply, but only very locally. The name "Waterstones" was given by Ormerod on account of a fancied resemblance to "watered" silk. Most of the Midland towns obtain their water from the Bunter (together with the Keuper occasionally), *e.g.*, Nottingham, Nuneaton, Worksop, Warrington, and, before they obtained a long distance supply, Manchester, Liverpool and Birmingham. An artesian supply from under glacial clay is obtained at Warrington.

9. Scenery. The Bunter and other sandy beds (*e.g.*, Arden Sandstone) are well wooded (Sherwood Forest, Forest of Arden, etc.), the Keuper forms lower agricultural or pastoral country. Some picturesque rocks, such as that on which Nottingham Castle stands, are sometimes formed by Bunter Pebble-Beds

LIFE OF THE PERIOD.

As with the Permian, the fauna and flora of the Triassic rocks of North-Western Europe is an impoverished one. In many ways intermediate between Palæozoic and Mesozoic the fauna seems to show sometimes greater affinities to the one, sometimes to the others, according to which group one studies.

a. Plants. Consist chiefly of Cycads (*Nilssonia*, *Otozamites*) and Conifers (*Voltzia*), with only a few ferns.

b. Vertebrata. Reptiles are far more abundant than in the Permian and marine forms (*Ichthyosaurus*) occur. Giant amphibia (*Mastodonsaurus*) are also typical, together with various fish.

c. Arthropoda. The Scorpions of the English Trias are interesting; true crabs and lobsters also appear in the Trias.

d. Mollusca. In the marine Trias both Lamellibranchs and Gastropods become numerous and varied, with an increase in siphonostomatous forms among the latter. Amongst Cephalopods the forerunners of Belemnites appear and Ceratites are important Ammonoids.

e. Brachiopoda. *Athyris* and other Palæozoic genera exhibit curious modifications before they become extinct; the typical Mesozoic *Terebratula* and *Rhynchonella* become common.

f. Echinodermata. The Cidaroids become very common. Among crinoids *Encrinus* may be noted.

g. Cœlenterata. Corals are almost entirely restricted to the Alpine type of deposit, they are more closely connected with the later Hexacoralla than with the Palæozoic Rugose corals.

CHAPTER XIII.

THE RHÆTIC SYSTEM.

In accordance with Continental usage and with the growing tendency in this country, the Rhætic is here considered as a separate system. In the British Isles, however, the system is not important, in it are included beds rarely exceeding 100 feet in thickness, and which behave more as the basal members of the Jurassic System. They mark the commencement of the Jurassic major Cycle of Sedimentation and pass up conformably into the overlying Lias. Previously the Rhætic has been classed with the Trias, but more often with the Jurassic.

GEOGRAPHY OF THE PERIOD.

The geography of the time is comparatively simple, and follows perfectly naturally when one considers that of the Upper Trias.

1. It has been seen that the earlier Triassic Beds were laid down in isolated basins, that these basins were partly filled up and gradually coalesced so that at the end of Keuper times one huge shallow lake covered a large part of the British Isles.

2. Now what would be the effect if, by the breaking down of some barrier to the south, or from some other cause, the sea broke into this area? It would naturally flow, perhaps quite gently, but rapidly and surely, over practically the whole of the Keuper Lake. This is precisely what happened in Rhætic times. The old Lake—almost a dry desert flat perhaps—was replaced by a shallow sea.

3. It is interesting to trace the effect of these changes on the existing Triassic fauna and on the invading Rhætic fauna. One can picture vast numbers of reptiles being

overwhelmed by the inrush of the sea, and their remains being mingled with those of fishes which may have been living in the Triassic Lake, and of fishes which, swept in with the sea, were unable to survive the conditions in the stagnant, salt-laden waters of the Lake. The hardier molluscs, brought in by the invading sea, also suffered, and for many generations survive only as small and stunted forms.

4. To be more exact, a very slight flexuring of the surface of the Triassic Marls seems to have left hollows, in which the earliest of the invading Rhætic molluscs lived and then left their remains to be buried in sediments differing but little from the underlying Keuper. This would account for the irregular distribution of the Rhætic deposits which underlie the main bone-bed. The importance of the bone-bed is doubtless accentuated by the lack of sediment during its deposition.

5. The higher Rhætic deposits become increasingly marine. It is probable that permanent connexion between the Keuper Lake and the outside sea was not obtained all at once.

THE RHÆTIC IN ENGLAND.[1]

The Rhætic System crops out across England from Devonshire to the Yorkshire Coast, following the outcrop of the lowest Jurassic beds, and gives rise to a small but usually well-marked ridge.

The succession is :—

2.	Upper	Watchet Beds, marls. Langport Beds, limestones ("White Lias"). Cotham Beds with Cotham marble.
1.	Lower	Westbury Beds or Black *Pteria contorta* shales, with the main Bone-bed at or near the base. Sully Beds—fossiliferous grey marls.

THE SULLY BEDS are found only at one or two points on either side of the Bristol Channel (Watchet in Somerset and Sully in Glamorganshire), and differ only from the Tea-Green Marls, which they succeed conformably and without marked junction, in the occasional presence of Rhætic lamellibranchs (*Chlamys valoniensis*,

[1] L. Richardson, *Quart. Jour. Geol. Soc.*, vol. lxi. (1905), pp. 374-430; vol. lxvii. (1911), pp. 1-74; *Proc. Geol. Assoc.*, vol. xix. (1906), pp. 408-409.

Protocardia rhætica, *Ostrea bristovi*, etc.), and the oldest known British mammal, *Microlestes*.

THE WESTBURY BEDS consist of black shales with numerous fossiliferous bands—some of which can be traced over large areas—with the famous Rhætic Bone-bed at or near the base. The Bone-bed consists of rolled fragments, often large, of reptilian bones, fish remains, teeth, etc., and rests unconformably on underlying beds. It is well seen at Aust Cliff on the River Severn, and also on the South Wales coast near Lavernock (Cardiff). Sometimes it passes laterally into a coarse sandstone (compare the Ludlow Bone-bed at the base of the Devonian). In some localities there is, however, a variable thickness of "Infra Bone-Bed" deposits classed with the Westbury Beds. Some of these contain hard bands crowded with tiny fossils, as at Blue Anchor Point (Somerset). Whether these beds are present or not there generally seems to be a ravinement at the base of the Westbury Beds, even when they rest on the Sully Beds. This is only natural when one considers the conditions under which they were formed. The Westbury Beds pass into beds of purely littoral character in certain places, especially round the Mendip Hills.

THE COTHAM BEDS are a series of greenish-yellow marls and limestones, with the curious "Cotham Marble" at or near the top. Again there is evidence of slight crustal movements—marked by the sudden change in the character of the beds from the underlying black shales. In the midst of the beds is a marl with ostracods, and, overlying it, a limestone locally rich in *Estheria* and plant remains. These deposits appear to have been formed very slowly. The Cotham Marble, with its arborescent or moss-like markings, has aroused much interest. It has been suggested that the markings were formed by bubbles of gas, originating in the lower layers of a soft creamy deposit, rising into higher layers, and there bursting and scattering minute specks of darker material. In places the bed appears to have been broken up and re-cemented ("False Cotham" of Aust Cliff). The Cotham Marble and associated beds are locally rich in *Pseudomonotis fallax* and insect remains. The upper surface of the marble is irregular, and frequently bored by lithophagous molluscs.

THE LANGPORT BEDS (*White Lias*) are pale-coloured limestones with bands of marl. Various lamellibranchs are common. The beds are locally absent, as in South Gloucestershire. The uppermost layer is the "Sun Bed" or "Jew Stone," whose upper surface is often waterworn and bored, especially when overlain directly by the *Ostrea* Beds of the Lower Lias.

THE WATCHET BEDS are local marly beds found in West Somerset and Glamorganshire above the true White Lias.

LIFE OF THE PERIOD.

Although allied to the succeeding Lower Lias faunas, the fauna of the Rhætic has many distinctive species, some of which, though numerically abundant in certain beds, have a short vertical range. As was the case with the fauna of the Ludlow Bone-bed

and the Lower Downtonian, it is probable that the Rhætic fauna of England could be divided into three groups :—

1. Triassic species which survived for a short time or were killed off by the change of conditions — most of the reptiles, and some of the fish.
2. Species which flourished under the changing conditions, and are peculiar to the Rhætic. Amongst these are some lamellibranchs, such as *Pteromya crowcombeia*. There are also those species characteristic of the Rhætic, not only in England, but also where it attains a much greater development, as on the Continent (*Pteria contorta*, *Chlamys* [*Pecten*] *valoniensis* and *Protocardia rhætica*).
3. Species which may be regarded as forerunners of succeeding faunas, and many of which persist into the Lias (*Ostrea liassica* in the upper part of the Rhætic, *Volsella minima*).

The presence of the earliest British mammal, *Microlestes*, in the Rhætic should be noted.

CHAPTER XIV.

THE JURASSIC SYSTEM.

NAME. The name Jurassic was adopted by Brongniart and Humboldt, and also by d'Orbigny from the Jura Mountains of Western Switzerland, where the rocks of this period are well developed. The rocks were early separated into three groups, Black Jura, Brown Jura and White Jura, corresponding to the Lower, Middle and Upper Jurassic respectively. In England the terms "Lias" for the lower division and "Oolites" for the middle and upper were long in use.

CLASSIFICATION.[1]

Upper Jurassic = Upper Oolites—mainly argillaceous.
Middle Jurassic = Lower Oolites—mainly calcareous.
Lower Jurassic = Lias—mainly argillaceous.

From the beauty and variety of their fossils the Jurassic rocks have long attracted attention. They have been more carefully studied and more minutely subdivided than any other system of rocks. The method of zoning by means of fossils—particularly by Ammonites—was applied to these rocks as early as 1856 by Oppel, and even earlier by Williamson in 1834.

HISTORY OF THE PERIOD.

It is possible to make certain generalizations :—

1. The period on the whole was one of quietude; but small earth-movements were going on almost continuously, not, however, reaching any great climax.

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[1] For details of the Jurassic in England, see C. Fox-Strangways and H. B. Woodward, "The Jurassic Rocks of Britain," *Mem. Geol. Surv.* (1892-5), vols. 1-5; for later work see W. J. Arkell, "The Jurassic System in Britain," *Oxford*, 1931.

2. There was no volcanic activity.
3. The great mountain chains, which arose at the end of the Carboniferous had been worn down very much in Permian and Triassic times, in the Jurassic, therefore, they were represented by mere stumps. Thus the Jurassic seas were largely but not entirely surrounded by comparatively low lands. The sediment which came down from the land was for the most part fine, or local in its distribution. It was therefore possible for shallow water limestones—almost free from muddy sediment—to be laid down quite close to shore lines, and for homogeneous clays to pass directly into littoral conglomerates almost without the intervention of a sandy facies. At certain times forested coastal swamps also developed.
4. It will be readily appreciated that even quite small earth-movements could produce extensive changes in the distribution of land and water.

The Jurassic System will be considered in three portions—Lower, Middle and Upper.

LOWER JURASSIC OR LIAS.

NAME. Lias is an old quarryman's term for a hard limestone, and was applied originally to the hard bands at the base of the formation (White Lias) and to the calcareous beds at a higher level (Blue Lias). It was gradually extended to include higher and higher beds. Curiously enough the most typical "lias" beds —the White Lias—are now removed from the Jurassic and considered as Rhætic.

GEOGRAPHY OF THE LIAS.

1. It has already been noticed that the Rhætic Sea broke into the Triassic Salt-lake and spread over a considerable part of it. Possibly this was but a temporary incursion, and permanent connexion with the main ocean was not at once established. This, together with the adverse conditions produced by the mingling of sea waters and the salt waters of the old lakes, may explain the poverty of the Rhætic fauna in England.

2. The opening of the Liassic period simply marks a continuation of the Rhætic invasion. The Liassic Sea

spread all over the area occupied by the Keuper Lake, and in places extended farther. Possibly the surface level of the Keuper Lake was below that of the main oceans, just as the Caspian Sea is at the present day. The invading sea would naturally enlarge the borders of the lake where the surrounding coast lands were flat, but not where it was bordered by mountains. Thus the Lias does not overlap the Keuper to any great extent against the old mountains of Wales; but, in places against the old ridge of Central England, it does.

3. The Liassic Sea, then, covers approximately the same area as the Keuper Lake (see Map, *Fig.* 51).

4. Of the surrounding lands and islands one may note that—

a. Devon and Cornwall probably formed a peninsula with the Liassic sea running up in large bays and gulfs to the north and south.[1]

b. Wales must have formed a mountainous area with a much greater elevation than at present. Round its southern borders the Lower Lias clays and limestones actually pass laterally into coastal deposits—well seen on the South Wales Coast—of hard conglomeratic limestones.

c. A great bay covered the Irish Sea and the North-East of Ireland, and stretched up the west coast of Scotland. Here the representatives of the Lias include conglomeratic limestones and thick sandstones. In Sutherland there are definitely estuarine beds. It is probable that a large river flowed southwards into the Liassic sea.

d. The Highlands of Scotland formed part of a great land mass.

e. A Palæozoic massif occupied Eastern England and Belgium. The Liassic deposits overlap the Triassic on all sides of this ridge, showing that the land cannot have been very high. The main mountain range of the land probably stretched from near London, running east and then south-east to include the Ardennes. Liassic deposits thin out against this land from all directions.

f. The Mendip Hills formed a group of islands. The Lower Lias clays pass laterally into hard massive limestones, and then into conglomerates as they are traced towards the islands. The conglomerates consist of pebbles of Carboniferous Limestone and chert. Remains of land

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[1] By a careful petrographical analysis, Professor P. G. H. Boswell has shown that the Liassic and Inferior Oolite Sands appear to be derived, in the West of England, from the west and south-west—from rocks resembling the pre-Cambrian of the Lizard or Western Brittany (see *Geol. Mag.*, vol. lxi., 1924, p. 262).

FIG. 51. The Liassic Sea. Existing outcrops in black. Axes of uplift or small deposition :—1, Market Weighton. 2, Oxfordshire. 3, Mendips. 4, London-Belgium Ridge. (*L.D.S.*)

insects are found in the calcareous muds of the Upper Lias deposited round the islands.

It should be noted that the shore-beds are mostly of Lower Lias age. The Middle and Upper Lias may have transgressed somewhat more extensively. Coastal deposits of Middle Lias age are known on the West Coast of Scotland.

5. The conditions prevalent in early Liassic times were such as to permit the formation, over a great part of the area, of alternating bands of blue-grey shale or clay and compact grey argillaceous limestone, each band varying from a few inches to a foot or more in thickness. The stratification is curiously regular, though the surface of the limestone bands may be smooth, ridged, ripple-marked or hummocky. A complete explanation of this deposition has not been given. The limestones are probably of the nature of calcareous muds of detrital origin.

6. The deposits of the Lias may be briefly summarized: clays in the Lower Lias; sandy clays and calcareous beds ("marlstone") in the Middle Lias; clays passing up into sands in the Upper Lias.

7. The existence of slight intra-Liassic folding movements has recently been proved. They can only be detected by a study of the variation in thickness of the sub-zones.

ZONES.

Before proceeding to an account of the Lias of England some notes on the different meanings of the word "zone" may be useful.

A zone may be defined as "the deposit formed during a given time. It is not the time, nor is it the series of fossils. A zone, once defined, is theoretically fixed for ever." A succession of zones in the Lias was originally proposed by Oppel in 1856-8. Great confusion has arisen from the fact that numerous authors have divided or discarded certain of Oppel's zones and intercalated others. Some of his zones may be cumbersome, but the only way to avoid confusion is to retain the original zones used by Oppel. They may with advantage be grouped into series (main zones or groups of zones) as the Geological Survey has done; further there is nothing to prevent Oppel's zones being split into as many sub-zones and hemeræ as one may like. This has, indeed, been done, but Oppel's zones must be retained as a basis. (Compare the discussion of zones on p. 24.)

CLASSIFICATION OF THE LIAS.

Survey.	Oppel's Zones.	Survey's Groups
UPPER LIAS (TOARCIAN)	*Lytoceras* [*Am.*] *jurensis*	*jurensis.*
	Posidonomya bronni	*communis.* *serpentinus*
MIDDLE LIAS (DOMERIAN)	*Paltopleuroceras* [*Am.*] *spinatum*	*spinatus.*
	Amaltheus [*Am.*] *margaritatus*	*margaritatus.*
LOWER LIAS	*Deroceras* [*Am.*] *davæi*	*capricornus.*
	Tragophylloceras [*Am.*] *ibex*	*jamesoni.*
	Uptonia [*Am.*] *jamesoni*	
	Deroceras [*Am.*] *armatum*	
	Echioceras [*Am.*] *raricostatum*	*oxynotus.*
	Oxynoticeras [*Am.*] *oxynotum*	
	Asteroceras [*Am.*] *obtusum*	
	Pentacrinus tuberculatus	*bucklandi.*
	Coroniceras [*Am.*] *bucklandi*	
	Schlotheimia [*Am.*] *angulata*	
	Psiloceras [*Am.*] *planorbis*	*planorbis.*

NOTES.

a. Fortunately the Liassic zones are usually known simply by the specific name of the zone fossil.

b. The most important points to remember about the Lias are contained in the diagrammatic section across England (*Fig.* 52).

c. In view of the varied classifications in use for the Lias, the student is advised to commit to memory either the Survey's groups of zones or else Oppel's zones, and, whenever referring to the zones of the Lias, to state in which sense the zonal designation is used. Thus: "In the *oxynotus* zone (of Oppel) . . ."

d. The "Middle Lias" of continental authors includes all zones from *armatum* (Oppel) to *spinatum* (Oppel), and hence Domerian is conveniently used as distinguishing in which sense "Middle Lias" is used.

e. The Lower Lias of English authors is divided into Hettangian, Sinemurian and Charmouthian.

f. Between the Middle and Upper Lias are interesting "Transition Beds," in which two sub-zones are generally recognized, viz., *acutus* (=top of Middle Lias) and *annulatus* (=base of Upper Lias).

g. At the base of the Lias are beds without Ammonites, but with abundant *Ostrea liassica.* They are generally known as the Pre-*Planorbis* or *Ostrea* Beds.

THE LIAS OF THE BRITISH ISLES.

The following remarks are in the nature of a brief commentary on the section (*Fig.* 52).

1. South Coast.

A fine section is exposed in the Charmouth and Lyme Regis Cliffs.

The Lower Lias has the characters which it preserves in the greater part of its outcrop across Britain—alternating clays and limestones (Blue Lias) in the lower part, followed by clays. The latter are separated on the Dorset Coast into Black Marls, Belemnite Beds and Green Ammonite Beds (ascending succession).

The Middle Lias consists of blue clay in the lower part, followed by micaceous sands, and then by yellow sands with doggers (note that the latter represent the " marlstone " and ironstone of the Midlands).

The Upper Lias. The lower zone is represented by less than three feet of strata, the upper zone by blue clay followed by sands (lower part of the Bridport Sands).

2. Coast of Bristol Channel — Somerset and Glamorgan.

A good section of the lower part of the Lower Lias is exposed.[1] The Glamorgan Coast is interesting in that it exhibits the overstep of the Lower Lias over the Rhætic and the coastal deposits of the former (=Southerndown and Sutton Beds) resting on Trias or on Carboniferous Limestone.

3. The Mendip Area (Radstock District).

This seems to have been a region of gradual uplift. The whole of the zones of the Lower Lias are represented by about 40 feet of limestones; the Middle Lias is largely absent, the Upper Lias consists of the " Cephalopod Bed " ($1\frac{1}{2}$—3 feet) below and the Midford Sands above. Between the Mendip Area and the Dorset Coast the Yeovil Sands and Ham Hill Stone represent the higher beds of the Upper Lias. It should be noticed that there is a thinning of the various members both from north and south, as the axis is approached (as at Radstock) and beds of littoral type are developed when Lias actually rests on the Mendips (as at Shepton Mallet).

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[1] A. E. Trueman, *Proc. Geol. Assoc.*, vol. xxxiii. (1922), pp. 245-284.

4. Gloucestershire.

The Lower Lias clays are again thick; as are also the micaceous sandy clays of the Middle Lias. A rock-bed appears in the upper part of the Middle Lias. The *bronni* zone of the Upper Lias is represented by some curious fish and insect beds at the base, followed by a few feet of clay, and then by some 265 feet of sands (Cotteswold Sands). The three-foot "Cephalopod Bed" represents the *jurensis* zone.

5. Oxfordshire.

Like the Mendip Hills, Oxfordshire was also a region of intra-Liassic uplift. Probably only the upper part of the Lower Lias is represented by the grey clays. In the Middle Lias the sandy clays are still present, and the rock-bed at the top in Gloucestershire has become the valuable Banbury Iron Ore. Then there seems to be a break (after a thin representative of the *acutus* sub-zone), and a few feet of blue clay (*communis* zone) are all that remain of the Upper Lias.

6. Northamptonshire.

The Lower Lias, as usual, consists of the interbedded limestones and shales below, followed by a thick series of clay, the monotony of which is relieved by a thin band of ironstone—the Plungar Ironstone—in the middle. The Middle Lias closely resembles that of Oxfordshire, it is curious that the "marlstone," so valuable as an iron ore, becomes locally too poor in quality to be of use. The higher beds of the Upper Lias are absent.

7. Lincolnshire.

The Lower Lias clays include the Frodingham Iron Ore, which becomes important north of Lincoln, whereas the Middle Lias Ironstone of great value south of Lincoln is of little value further north. The higher part of the Upper Lias is again absent.

8. Yorkshire.

The Lower Lias is represented by shaly clays, often with bands of limestone and ironstone doggers. The

Middle Lias consists of sandy clays with the valuable Cleveland Ironstone in the upper part. The Upper Lias comprises a fairly complete sequence, well seen on the coast near Whitby, of shales in the lower part and sands (Blea Wyke Beds) above. The shales include the famous "Jet-rock" and Alum Shales of Whitby. The Market Weighton axis of uplift in South Yorkshire, comparable with the Mendip and Oxfordshire axes, should be noted.

9. Kent Coalfield.

As there is a representative of the Keuper underground in East Kent, and as the Liassic deposits occupy approximately the same area as the Keuper Lake, there is also a thin representative of the Lias, wedging out to the north.

10. West Coast of Scotland (Mull, Skye, Raasay, etc.).

Fragments of Liassic rocks also occur in the agglomerates filling up the Tertiary necks as in Arran. In Raasay the Lower Lias is represented by limestones with *Ostrea liassica* passing up into sandstones, and then into a great series of shales (Pabba Shales, 600 feet). The Middle Lias comprises the Scalpa Sandstone, whilst the Upper Lias has some shales at the base followed by the Raasay Oolitic Iron Ore. The latter is about eight feet thick, and consists of a green iron-silicate allied to glauconite.

11. East Coast of Scotland (Sutherland).

The Lower Lias is represented by a series of estuarine sandstones and shales with thin coals, followed by shales.

12. Ireland.

A few small areas of Lower Lias clay are found beneath the protective covering of the Antrim Basalts. The higher part of the Lower Lias and succeeding beds are wanting.

It should be noted that there are three areas where the Lias is relatively thin, separated by regions where a

very considerable thickness is present. The former are regions of uplift which persisted during Jurassic times: the Middle and in one case Upper Jurassics tend to be thin or incomplete in the same areas (see *Figs.* 52 and 53, but contrast *Fig.* 55).

ECONOMIC GEOLOGY OF THE LIAS.

1. Lime and Cement. Hydraulic lime is made from the limestones at the base of the formation, hence the beds are often referred to as the "Hydraulic Limestones."

2. Building Stone. Not important, stone is quarried locally as at Shepton Mallet, and the Hornton Stone comes from the Middle Lias, near Banbury.

3. Road Metal. The Lower Lias Limestones are not good road stones, they powder too easily, giving rise to a fine white dust in summer and a sticky grey mud in winter.

4. Brick and Tile Clays. Articles made from Liassic Clays (zones *oxynotus* to *capricornus*) are usually red. The Lower Lias clays are frequently used, as in Lincolnshire.

5. Sands. None of importance.

6. Lignites, etc. The collection of jet from the Upper Lias and its manufacture into articles was formerly an important industry of Whitby. The trade was worth £90,000 in 1873, but is now practically nil, owing to the decline in use of jet ornaments Alum was formerly manufactured from the Alum Shales of Whitby.

7. Iron Ores are extremely important, and furnish the bulk of British Iron Ore.

Lower Lias. The Frodingham Ironstone of Lincolnshire occurs in the *tuberculatus* zone (Oppel). It is an oolitic, calcareous ore, up to 32 feet in thickness. First worked in 1859, it now produces about 20 per cent. of the British output of ore.

It is too calcareous to be smelted alone, so it is often mixed with siliceous ore from the Northampton Sands formation (Interior Oolite).

Middle Lias. Included here are the valuable Cleveland ores of Yorkshire and the ores of Mid-Lincolnshire, East Leicestershire and Oxfordshire. When fresh these ores are greenish-grey, but weather to a limonitic brown. They consist chiefly of carbonate of iron coloured by a silicate. In the Cleveland District there are several seams :—

Upper Lias	
Main Seam	6—11 feet.
Shale	
Pecten Seam	1½—6 feet.
Shale	
2-foot Seam	1½—2½ feet.
Shale	
Avicula Seam	0—3 feet.

Upper Lias. Includes the Raasay Ore, which is too far removed from the principal smelting regions to be of much commercial value.

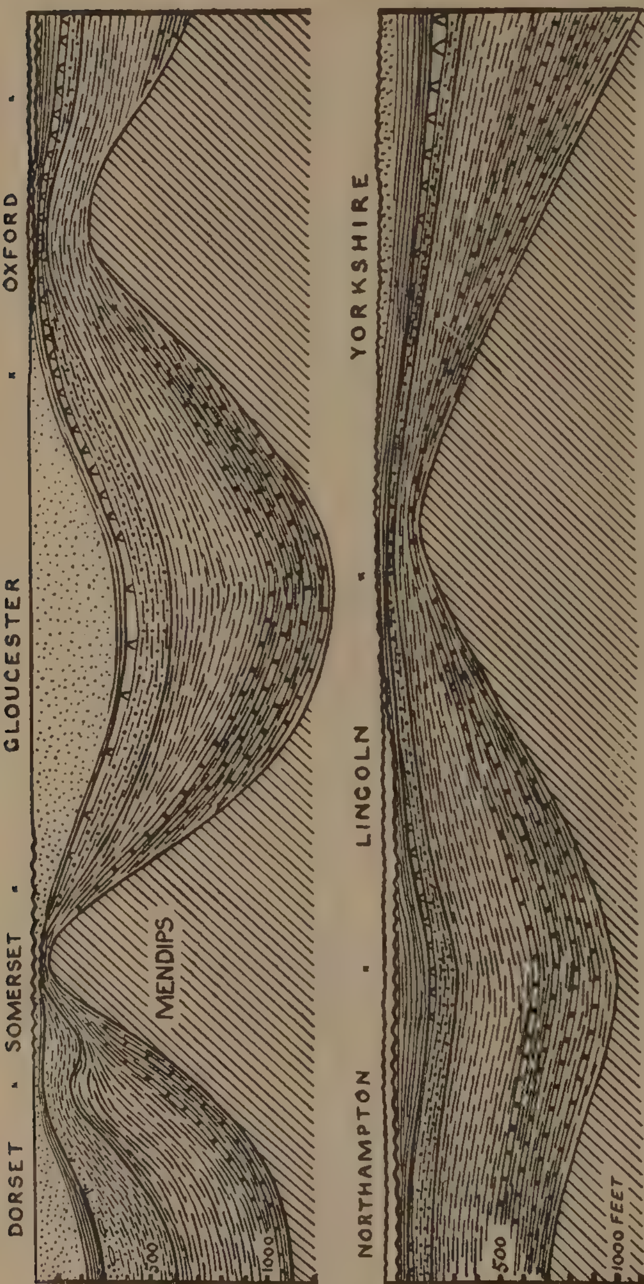

FIG. 52. Diagrammatic Section through the Lower Jurassic (Liassic) deposits of England. The heavier lines indicate the junctions between Lower, Middle and Upper Lias. Horizontal Scale approximately 25 miles=one inch. (*L.D.S.*)

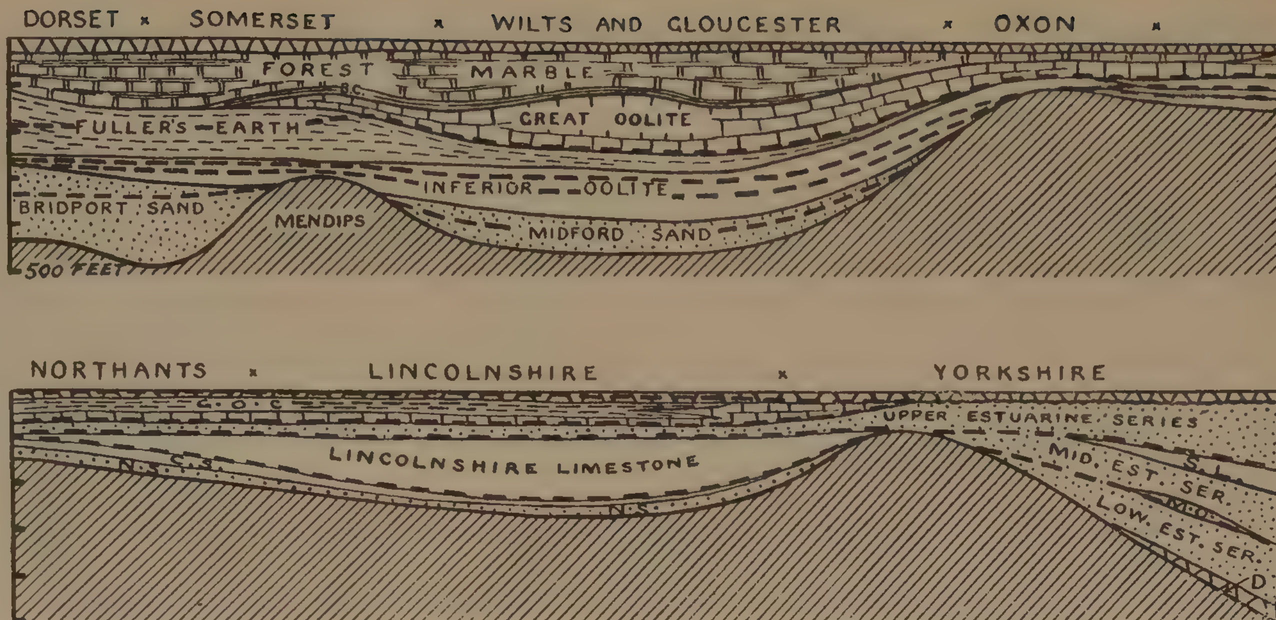

FIG. 53. Diagrammatic Section through the Middle Jurassic deposi'ts of England. B.C. = Bradford Clay; N.S. = Northampton Sands; C.S. = Collyweston Slate; G.O.C. = Great Oolite Clay; D = Dogger; M.O. = Millepore Oolite; S.L. = Scarborough Limestone. The heavy interrupted lines show the division into Aalenian, Bajocian, Vesulian and Bradfordian. Some Liassic (pre-Aalenian) beds are included in the lower part of the Bridport and Midford Sands. The highest bed shown (Cornbrash) belongs to the Uppe Jurassic in Yorkshire. (Adapted from *Lake* and *Rastall.*)

8. Water. Many villages obtain their supply from springs issuing out at the junction of the Inferior Oolite or Upper Lias sands and the Upper Lias clays. The Middle Lias marlstones and underlying sandy beds yield a supply which is generally good, and becomes important at Banbury and Grantham.

9. Scenery and Agriculture. The Middle Lias marlstone generally gives rise to an escarpment, the clays to low ground. The heavier clays are usually given over to pasture land, other beds form good rich arable land.

NOTE ON THE FOSSILS OF THE LIAS.

Apart from zonal forms, the following are some of the more important Liassic fossils:—

LOWER LIAS. *Calcirhynchia* [*Rhynchonella*] *calcicosta;* the lamellibranchs *Cardinia listeri, Hippopodium ponderosum, Oxytoma* [*Pteria*] *inequivalvis, Ostrea liassica, Plagiostoma gigantea,* and *Gryphea arcuata,* the reptiles *Plesiosaurus* and *Ichthyosaurus* (the teeth especially should be noted).

MIDDLE LIAS. Brachiopods: *Spiriferina Walcotti, Cincta* [*Waldheimia*] *numismalis, Waldheimia resupinata, Tetrarhynchia* [*Rhynchonella*] *tetrahedra, Homœorhynchia* [*R.*] *acuta;* the lamellibranchs *Oxytoma* [*Pteria*] *cygnipes, Pecten æquivalvis.*

UPPER LIAS. Lamellibranchs, *Leda ovum,* and *Protocardia truncata.*

MIDDLE JURASSIC (LOWER OOLITES).

NAME. A very common lithological type is an oolitic limestone, hence the name "Oolites."

GEOGRAPHY OF THE MIDDLE JURASSIC.

1. Having in mind the Liassic Sea, which covered practically the same area as the old Triassic Lake, the changes of Middle Jurassic time are not difficult to understand.

2. Contemporary uplift along certain lines in Liassic time has already been noted. Minor folding along these same lines—apparently old east-west Armorican axes—took place especially in the earlier half of the Middle Jurassic (Bajocian). The results were—

a. The sea bottom was divided up into a number of synclinal basins, not necessarily entirely separated from one another, but so that the deposits in one syncline differed very considerably from those in the next.

b. Local unconformities—in some localities the upper beds of the Lias were removed before the deposition of the Bajocian, in other localities there is a perfect transition.

c. Contemporaneous denudation and local non-sequences.

d. A shallow sea disturbed by changing currents. Both the limestones and sands tend to be false-bedded.

3. Very slightly later[1] a general tilt took place, causing uplift in the north and depression in the south. This caused—

a. Much coarser sediment—sands, etc.—and estuarine conditions in the north.

b. Overlap of sea in the south (Kent Coalfield and France).

4. The combined effect of the two movements produced local swampy flats — almost like Coal Measure estuarine areas—as in Yorkshire, and, further south, sheltered marine lagoons. Locally coral reefs flourished, the debris of which furnished the calcareous material for the formation of oolitic limestones. The conditions compare most closely with a gulf on the Australian Coast, and it is curious that the faunas are in some measure comparable. The typical marine faunas (ammonites, etc.) flourished in the south; reptiles and even mammals wandered round the lagoons of Central England; whilst plant remains were entombed in the estuarine beds of the north.

5. At the end of the Middle Jurassic period tranquil marine conditions prevailed over the whole country, and the Cornbrash was laid down—a thin deposit, but one which varies but little from Dorset to Yorkshire. There is, however, an important palæontological break in the middle of the Cornbrash.

THE MIDDLE JURASSIC IN GREAT BRITAIN.

The classification generally adopted at the present day is as follows:—

		Old Zones.
2. Bathonian or Great Oolite	Bradfordian.	
	Vesulian,	*Am. parkinsoni.*
1. Bajocian (*sensu lato*) or Inferior Oolite	Bajocian, *sensu stricto.*	*Am. humphresianus.*
	Aalenian,	*Am. murchisonæ.*

Again the relationship between the varied beds is best expressed by a diagrammatic section from Dorset to Yorkshire (*Fig.* 53). The following account is a commentary on the section, details of unconformities shown there are not mentioned in the text. It will be noticed

[1] Probably in Early Bathonian times, since on the West Coast of Scotland the Bajocian is represented by a thick series of marine limestones, the Bathonian by deltaic deposits of sand.

that the section comprises—*a*. synclinal basins or areas of depression; *b*. areas of contemporary uplift or non-subsidence. They will be described in that way.

1. Dorsetshire Depression.

AALENIAN: lower part formed by upper part of Bridport Sands. Upper part or Lower Inferior Oolite comprises variable beds, mainly limestones.

BAJOCIAN: thin variable beds, mainly limestones (Middle Inferior Oolite).

VESULIAN: lower part formed by Upper Inferior Oolite, upper part by the Lower Fuller's Earth Clay.

BRADFORDIAN (or Bathian): Fuller's Earth Rock and Upper Clay, followed by *Rhynchonella boueti* bed, and then by Forest Marble (a shelly, oolitic limestone) and Cornbrash.

Passing northwards into Somerset and Wiltshire, the Ironshot Oolites of Dundry represent the Bajocian, with a small gap at the top; in the Bradfordian the Great Oolite takes the place of the Fuller's Earth Rock and Upper Clay, and the Bradford Clay that of the *Rhyn. boueti* bed.

2. Mendip Axis of Uplift.

The striking difference between the brachiopod faunas of the Aalenian and Bajocian in the Dorset and Gloucester provinces shows that free communication could not then have existed. The lowest beds of the Jurassic present at certain places in the Mendip Hills (Nunney and Vallis, etc.) are Vesulian.

3. Gloucestershire Depression.

AALENIAN and BAJOCIAN: a varied series of sands, limestones, and granular rubbly limestones (so-called "grits"), many of which have received special names (such as Upper and Lower Freestone in the Aalenian, Lower *Trigonia* Grit, Gryphite Grit and Notgrove Freestone in the Bajocian). There is a small gap at the top.

VESULIAN: includes the Upper *Trigonia* Grit, *Clypeus* Grit, Chipping Norton Limestone and Fuller's Earth Clay.

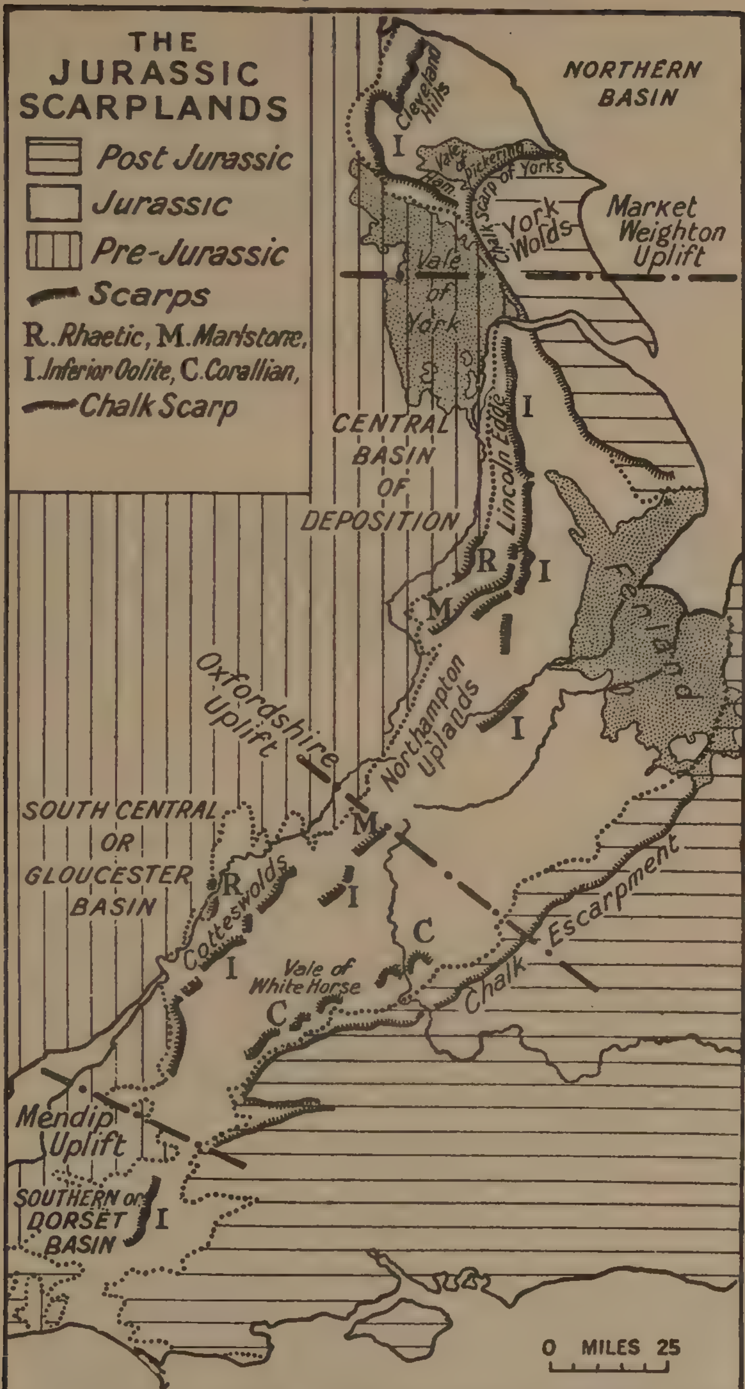

FIG. 53a. The scarplands of the south-east of England, showing the relation between the existing scarps and the original basins of deposition. (From Stamp and Beaver's *The British Isles*, by permission of Longmans, Green and Co., Ltd.)

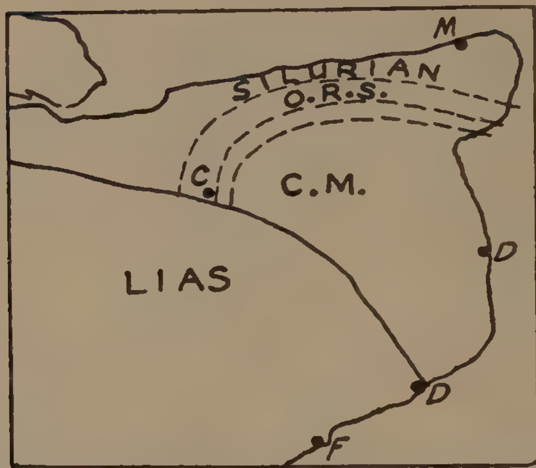

FIG. 53b. Diagrammatic map showing the "feather edge" of the Liassic deposits on the palæozoic platform of East Kent (p. 220).

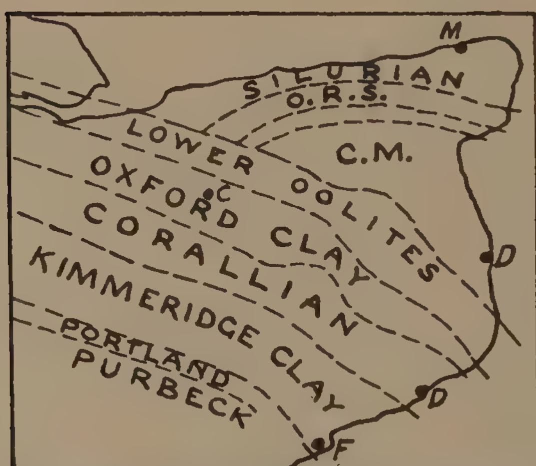

FIG. 53c. Diagrammatic map showing the disposition of the post Liassic Jurassic rocks on the palæozoic platform of East Kent, supposing the later Cretaceous rocks have been removed.

BRADFORDIAN: Great Oolite (oolitic and shelly limestones), with the Stonesfield "Slate" (thin bedded limestone) at the base, followed by Bradford Clay (3—8 feet), Forest Marble and Cornbrash.

4. Oxfordshire Axis of Uplift.[1]

AALENIAN and BAJOCIAN: entirely absent.

VESULIAN: represented by *Clypeus* Grit, Chipping Norton Limestone and Neærean Beds.

BRADFORDIAN: as in Gloucestershire, but Bradford Clay absent.

5. Northamptonshire and Lincolnshire Depression.

AALENIAN: lowest beds absent, the older strata of this age being the variable Northampton Sands, with ironstone beds and marine fossils, but passing up into the Lower Estuarine Beds, capped by the Collyweston "Slate" (thinly bedded limestone).

BAJOCIAN: represented by the massive Lincolnshire Limestone.

VESULIAN: represented by the Upper Estuarine Beds.

BRADFORDIAN: Great Oolite Limestone, followed by Blisworth Clay and Cornbrash. Palæontologically only the lower part of the latter is Bradfordian, the upper part belongs to the Upper Jurassic.

6. Market Weighton Axis of Uplift.

This is the one great area of uplift or non-subsidence which persisted throughout Jurassic times, interrupting even the Oxford Clay which was deposited evenly over the Mendip and Oxfordshire axes. The Axis runs approximately east and west to the north of the Humber, and there is a very great contrast in the beds on either side.

7. Yorkshire Depression.

AALENIAN: Lowest beds probably unrepresented; "Dogger" and Lower Estuarine Beds.

BAJOCIAN: Millepore Oolite (marine), followed by

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[1] "Geology of the Country around Oxford," *Mem. Geol. Surv.*, 1908; W. J. Arkell, "The Geology of Oxford," 1947.

Middle Estuarine Beds, capped by Scarborough Limestone.

VESULIAN: Upper Estuarine Beds.

BRADFORDIAN: absent.

8. West Coast of Scotland.

AALENIAN: Sandy micaceous shales.

BAJOCIAN: Sandstones and shales with marine fossils.

VESULIAN: Marine limestones at the base, followed by Estuarine Beds with thin coals.

BRADFORDIAN: Absent or represented in part by the Estuarine Beds.

9. East Coast of Scotland.

About 230 feet of Estuarine Beds (base not seen), with the Brora Coal (3 feet) at top, seem to represent the Vesulian.

10. Kent (Underground).

The old ridge between Eastern England and Belgium, like the old ridge of the Mendip Hills, underwent periodic uplifts during the Jurassic Period. The upper part of the Lias was denuded away, and locally in Kent (as at Brabourne) a few feet of oolitic limestone (Bajocian or Vesulian) come between the Lias and the Bathonian. The Bathonian trangression is marked by the occurrence of Bradfordian resting directly on Old Red Sandstone in the London district. It is overlain there by Cretaceous. In the same way to the north of the ridge, as at Calvert (Bucks), the Vesulian (Chipping Norton Limestone) rests directly on Middle Lias. On the whole there was a steady transgression north-north-eastwards in East Kent against this ridge from Bradfordian to Purbeckian times, but the effects of periodic uplifts of the ridge are seen in local unconformities and absence of certain beds (*e.g.*, highest part of Kimmeridge Clay).

NOTES.

1. The classification of the Middle Jurassic is now on a strictly palæontological basis.

2. In many ways the classification is impracticable. Thus the group of sands—locally known as the Midford, Bridport

and Cotteswold sands—which occupy the higher part of the Upper Lias and the lower part of the Aalenian are not constant in their position in the zonal scheme. Yet in mapping they cannot be divided into an Upper Lias part and an Aalenian part, and must be mapped as a whole.

3. The same applies to the division between the Aalenian and Bajocian. It may be found in a single block of stone.

4. That valuable datum line, the Cornbrash, is also not constant in its horizon, but is younger in the north than in the south.

ECONOMIC GEOLOGY OF THE MIDDLE JURASSIC.

1. Lime and Cement. Lime-burning is carried on at numerous places. It is found that the relatively impure compact limestones yield a "stronger" lime than the purer oolites.

2. Building Stones are very important.

a. Inferior Oolite is worked in two main areas.

(i.) Somerset and Gloucestershire; various beds in the Aalenian used in the Dundry, Stroud and Cheltenham districts. The Lower Freestone is one of the principal Cotteswold Building Stones. The Bajocian stones occur in the same localities, but are not so good, being more of the nature of "ragstones."

(ii.) Rutland and Lincolnshire; the higher beds of the Aalenian yield the highly fissile sandy limestone known as the Collyweston Slate in the Stamford district. This is still prized as a pretty roofing slate. The Bajocian Lincolnshire Limestone yields the fine oolite of Ketton, Stamford and elsewhere—a magnificent freestone. Of historic interest are the Weldon Stone used in Old St. Paul's and Barnack Stone used in Peterborough and Ely Cathedrals from the same horizon. A more compact variety yields the Stamford Marble.

b. Great Oolite is important in one main area—from Bath to Oxfordshire. The Vesulian, however, yields the famous Doulting stone in Somerset, and the Chipping Norton Limestone is quarried at various localities. In the Bradfordian the Bath stone is a magnificent freestone, much quarried round Bath and Minchinhampton. The Stonesfield Slate is used for roofing purposes in the same way as the Collyweston Slate. The Forest Marble is also occasionally quarried for building stone.

3. Road Metal. Most of the Middle Jurassic limestones are much used locally.

4. Sands. A little moulding sand is obtained from the Upper Estuarine Beds at Huttons Ambo, North Yorkshire, and can also be used for glass manufacture. Other glass sands occur in the Lower Estuarine.

5. Fuller's Earth is obtained from the Bradfordian of Somerset and Gloucestershire.

6. Clays, etc. Clays are used in various places for the manufacture of coarse red-ware (tiles, etc.). At Stamford a mixture of clays is used. A little fire-clay is obtained from the Upper Estuarine Series.

7. Iron Ores. The Northamptonshire Iron Ore (Aalenian) is a siliceous ore, oolitic in texture and gritty with quartz grains. In depth—as seen in wells and mines—it is greenish grey and calcareous. It is the most important iron-ore in Britain.

8. Water. Most of the sandy strata are waterbearing. The Oolites are also important, but the water from them suffers from temporary hardness. The supplies obtained from springs issuing from the base of the Inferior Oolite, where it rests on Upper Lias clays, have already been noted.

9. Soils. The "brashy" soils afforded by the weathering of the argillaceous and slightly ferruginous limestones are particularly good. The name "Cornbrash" implies their importance in agriculture.

10. Scenery. The Inferior Oolite Limestones usually give rise to a well-marked escarpment, both in the South-West and also in the Midlands and Lincolnshire (Lincolnshire Limestone). This is particularly the case when the underlying beds are calcareous sands, which often stand up almost vertically. The picturesque sunken lanes are also exemplary of the last-mentioned characteristic. The ridge running north and south through Lincoln and breached by the River Welland is a good example of the escarpment of the Lincolnshire Limestone.

NOTE ON THE FOSSILS OF THE MIDDLE JURASSIC.

Some of the more important, not already mentioned are:—

AALENIAN and BAJOCIAN. The plant *Equisetites columnaris*: Echinoids, such as *Clypeus ploti*, *Holectypus hemisphericus*, and *Acrosalenia*; *Plectothyris* [*Terebratula*] *fimbria* and *Rhynchonella ringens*; the lamellibranchs *Lima gibbosa*, *Trigonia costata*. *Williamsonia pecten* and *Pholadomya fidicula*; and the gastropod *Nerinea*. Ammonites, noted above as old zonal forms, also *Ludwigia murchisoni*, *Perisphinctes humphresianus*, and *Lioceras opalinum*.

VESULIAN and BRADFORDIAN. FULLER'S EARTH: *Ostrea acuminata*. GREAT OOLITE: *Terebratula maxillata*. FOREST MARBLE and BRADFORD CLAY: *Apiocrinus parkinsoni* and *Ornithella* [*Terebratula*] *digona*. CORNBRASH: *Ornithella obovata*, *Goniomya literata*, *Chlamys* [*Pecten*] *vagans* and *Macrocephalites* [*Ammonites*] *macrocephalus*.

UPPER JURASSIC (UPPER OOLITES).

Unlike the preceding division, the Upper Jurassic is mainly argillaceous; there is scarcely a single horizon which is not represented somewhere in England by a deposit of clay. On the other hand, there is no place

where the whole series is clayey, everywhere there are great intercalations of limestone and sandstone, usually lenticular. The original classification of the beds was founded on lithology, and this is still the usual and almost the only practicable classification. The more exact palæontological divisions founded on the original lithological types have, unfortunately, received very different definitions in England and on the Continent. Thus we can safely refer to the "Oxford Clay," meaning thereby a lithological formation, but "Oxfordian (*sensu anglico*)" and "Oxfordian (*sensu gallico*)" are very different in meaning.

Outline Classification.

5. **Purbeck Beds.**
4. **Portland Beds.**
3. **Kimmeridge Clay.**
2. **Corallian Rocks and Ampthill Clay.**
1. **Kellaways Rock and Oxford Clay.**

The limit between the Upper Jurassic and the overlying Cretaceous is very difficult to define—

(a) In the South of England the lacustrine Wealden Beds—usually grouped as Cretaceous—form a natural continuation of the shallow water conditions of the brackish Purbeck Beds. The Wealden deposits form the natural closing phase of the great Rhæto-Jurassic Cycle of Sedimentation, and will be described in that connection.

(b) In the North of England the marine beds on the same horizon as the Purbeck and part of the Portland of Southern England form the natural base of the Cretaceous Cycle of Sedimentation, and will be described with the Cretaceous.

GEOGRAPHY OF THE UPPER JURASSIC.

1. After the varied changes during Middle Jurassic time, it has already been noted that the period closed with uniform marine conditions prevalent over the whole country from Dorset to Yorkshire (time of deposition of the Cornbrash).

2. The lowest beds of the Upper Jurassic (the Kellaways Rock) indicate a continuation of marine conditions, and, from the abundant Ammonite fauna as far north as Yorkshire, more favourable to marine life than was the Cornbrash. To the west, however, great deposits of

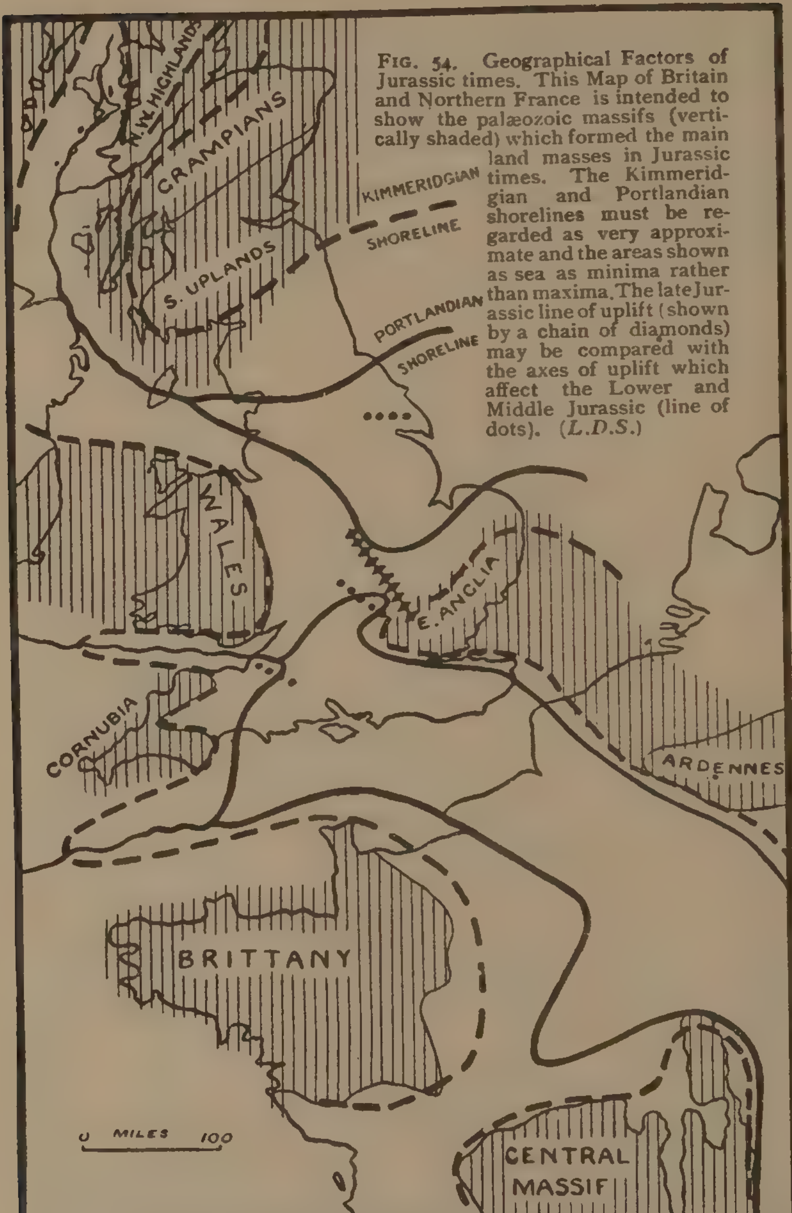

FIG. 54. Geographical Factors of Jurassic times. This Map of Britain and Northern France is intended to show the palæozoic massifs (vertically shaded) which formed the main land masses in Jurassic times. The Kimmeridgian and Portlandian shorelines must be regarded as very approximate and the areas shown as sea as minima rather than maxima. The late Jurassic line of uplift (shown by a chain of diamonds) may be compared with the axes of uplift which affect the Lower and Middle Jurassic (line of dots). (*L.D.S.*)

sand indicate either deltaic conditions or great shallow-water sandbanks, the material of which may have come from the Pennine Hills.

3. Then followed a great depression and a change of currents, so that the mud-laden waves of a dirty sea spread all over the country from Dorset to Yorkshire, and up the West Coast of Scotland, destroying the clear-water coral faunas of the Middle Jurassic depressions.

4. One of the great controlling factors of Upper Jurassic time was the very gradual, almost imperceptible, uplift of a ridge across England from north-west to south-east, or from west to east—following to some extent the ridge of Lower Carboniferous, Permian and Triassic times, or perhaps a still older Charnian axis. Exactly when this movement commenced is by no means certain, but one notices that in Corallian times the deposits were predominantly argillaceous (Ampthill Clay) to the north as far south as Oxfordshire, but further south the calcareous facies of the Coral Rag—with its abundant coral fauna—indicates clearer water. This may be due to the fact that the gradually forming ridge cut off the muddy waters coming from the north.

5. In the succeeding Kimmeridge Clay period a huge thickness of muddy sediment was laid down over all the British area. Though showing little variation in lithology, the thickness varies from 1,000 feet in Dorset to less than 100 feet in Bedfordshire, but increases to 500 feet in Yorkshire. It will be noticed from *Fig.* 55 that the Market Weighton axis of non-deposition still persisted, but that the Mendip and Oxfordshire axes were replaced by this new line running south-eastwards. Like the Oxfordian, the Kimmeridge sea extended right up the West Coast of Scotland to the East Coast.[1]

6. At the close of the Kimmeridge Clay period, or a little later, the Northern Sea was definitely cut off from the Southern.

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[1] Whilst no Kimmeridge Clay rocks are known on the West Coast, the connexion between the East Coast deposits and the main English area most probably was along the old Caledonian fold valley of the Great Glen, and down the West Coast, as in previous periods, rather than along the present East Coast of Scotland.

a. In the Northern Sea probably some Portlandian beds were laid down, but they were eroded away later, and the only remaining traces are some rolled Portlandian fossils of Russian affinities at the base of the Speeton Clay.

b. In the Southern Sea a series of calcareous sands is succeeded by shelly and oolitic limestone—the Portland Stone—showing that the source of the mud had been cut off, and the water was again clearer.

7. Subsequent History in the North. Possibly the North of England was raised above the level of the sea for a very short period in Portlandian times, or, in any case, the area came under the erosive wave action of the sea. The sea definitely returned in late Portlandian or Purbeckian times, and the deposition of the Speeton Clay commenced, a deposition which continued right into Cretaceous times. Further south, at the same time, sandy beds were laid down (Spilsby Sandstone of Lincolnshire).

8. Subsequent History in the South. The sheltered marine gulf of Portlandian times seems to have been cut off from the sea, and the succeeding Purbeck Beds consist of alternating estuarine and freshwater beds with marine intercalations. Here and there are " dirt-beds " —soils formed during terrestrial interludes. Then the Purbeck lagoon became further enclosed, and resulted in the Wealden " Lake." The latter may, however, have been open to the sea towards the south.

9. The close of the Jurassic Period was thus marked by a continental period — the natural end of the great Cycle of Sedimentation. Land covered the greater part of the South of England, but conditions were very different from those prevailing in the preceding land period —the Permian and Trias. The land was mostly low, and probably covered with a rich vegetation—damp, but not necessarily hot, jungles, through which rambled the great reptiles, such as *Iguanodon*.

THE UPPER JURASSIC IN GREAT BRITAIN.

The relation of the beds one to another is shown by means of a diagrammatic section (*Fig.* 55). It will be

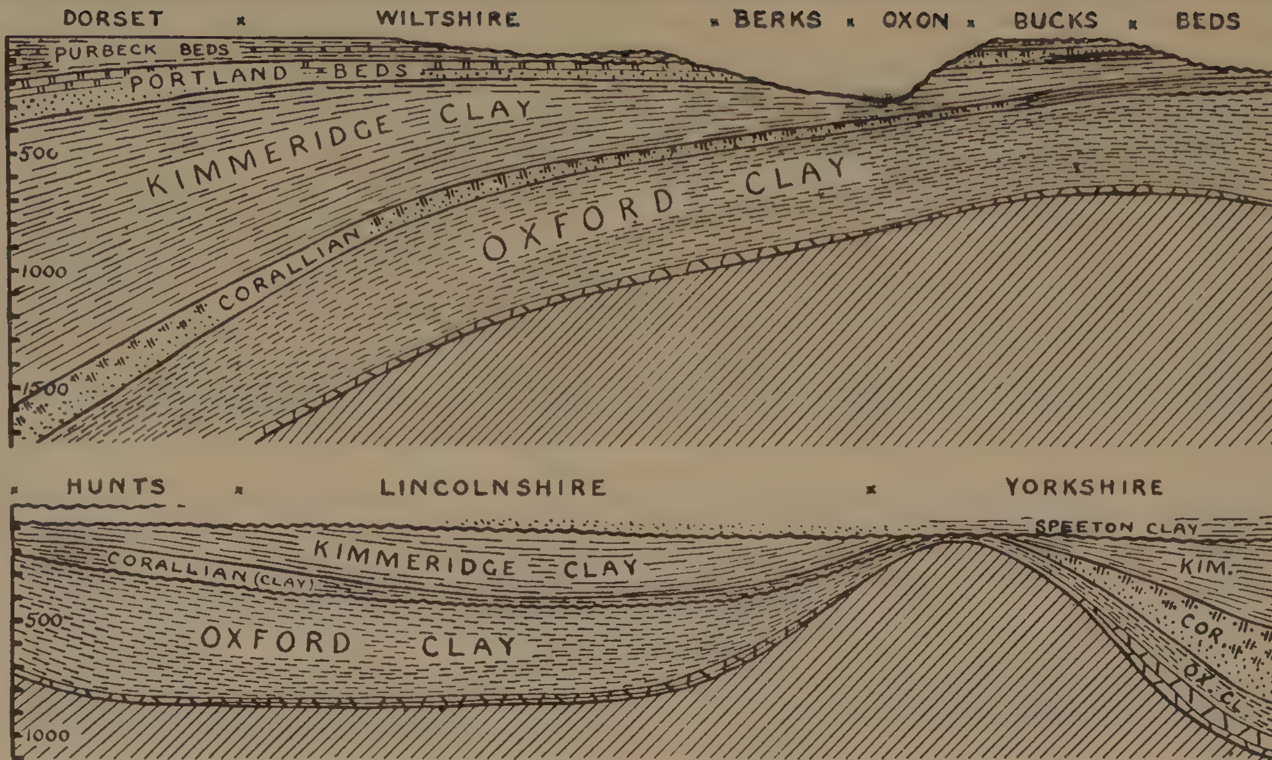

FIG. 55. Diagrammatic Section through the Upper Jurassic deposits of England. The lowest beds shown are the Kellaways Rock, underlain by part of the Cornbrash in Lincolnshire and the whole of the Cornbrash in Yorkshire. Notice the Market Weighton axis in South Yorkshire, in the same position as in Lower and Middle Jurassic. (*L.D.S.*)

noticed that England was not divided into basins of deposition in quite the same way as in Middle Jurassic times, and it will be simpler to consider each lithological division separately.

A. England.[1]

1. Oxford Clay with Kellaways Rock.

The Kellaways Rock is a calcareous sandstone, which forms a basement bed to the Oxford Clay. It usually rests directly on the Cornbrash, but may be separated by a variable thickness of "Kellaways Clay." It is richly fossiliferous, *Sigaloceras* [*Ammonites*] *calloviense*, *Gryphæa bilobata* and *Goniomya v-scripta* being characteristic, but exposures are rare. In Yorkshire the Cornbrash is palæontologically the base of the Upper Jurassic, and the Kellaways Rock includes zones which are represented by clay further south.[2]

The Lower part of the Oxford Clay consists of shaly clays with compressed fossils and stiff blue clays with pyritous fossils. *Cosmoceras* [*Ammonites*] *jason* in the lower part and *C. duncani* in the upper part are important. The Middle Oxford Clay is a dark clay, with some gypsum and many pyritous fossils, including *Peltoceras* [*Ammonites*] *athleta* (lower part), *Quenstedticeras* [*Ammonites*] *lamberti*, *Q. mariæ*, and *Belemnites hastatus* (upper part). The Upper Oxford Clay tends to be more shaly, and has large *Gryphæa dilatata*, *Cardioceras* sp., etc., *Belemnites oweni* is a large Belemnite characteristic of the Oxford Clay, and reptile remains also occur. In Yorkshire the whole part represented by clay corresponds to the Upper Oxford Clay of the south.

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[1] In view of the difference of opinion which exists concerning the zones of the Upper Jurassic and of the studies which are at present being carried out on this subject, no reference is made to "zones," but characteristic fossils, many of which have been used as zone fossils, are mentioned for different horizons of the formations described.

[2] Much useful information concerning the Upper Jurassic of Southern England is to be found in the "Geology of the Isle of Purbeck," *Mem. Geol. Surv.*, 1898; also in the little "Guide to the Geological Model of the Isle of Purbeck," 1906.

2. Corallian Rocks.[1]

a. CORALLIAN FACIES is the clear water facies of the South of England, but it reappears also in Yorkshire. The beds are very variable, but the usual sequence is—

Upper Calcareous Grit and Upper Coral Rag.
Coral Rag and Coralline Oolite.
Lower Calcareous Grit.

The lower division is a calcareous sandstone in which fossils are not very abundant, but include casts of a large ammonite, *Aspidoceras.*

The Coral Rag is a shelly limestone, locally beds of oolite occur, and occasionally seams of clay.

In the two upper divisions corals are abundant—*Thamnastræa* and *Thecosmilia annularis,* and huge numbers of the little lamellibranch, *Exogyra nana,* occur. Echinoids are locally very common, especially *Cidaris florigemma, Hemicidaris intermedia* and *Nucleolites scutatus.* The highest beds of the Corallian include deposits of oolitic iron ore at Abbotsbury, near Weymouth, and at Westbury in Wiltshire.

b. AMPTHILL CLAY FACIES in the Midlands. A few miles east of Oxford there is an abrupt change of facies, and the Corallian is represented by a grey or black clay full of gypsum. The most important fossil is *Ostrea discoidea,* but the fauna as a whole is a mixture of Oxford and Kimmeridge Clay species. There is often a rock bed at the base—the Elsworth Rock—and at Upware, near Cambridge, is a small patch of coral rag of southern type. The clayey facies seems to extend as far north as Yorkshire.

c. CORAL RAG FACIES of North Yorkshire. The series is very fossiliferous and thicker than in the South of England. There are three main masses of Sandstone (Calcareous Grits), separated by two masses of limestone.

3. Kimmeridge Clay.

This is one of the most constant and uniform formations in England—except as regards its thickness. It is a dark-grey or black clay, shaly and bituminous, especially

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[1] The recent work of W. J. Arkell on the Corallian should be studied. It is summarized in his "Jurassic System in Britain," 1931.

in the upper part. Layers of septaria and bands of argillaceous limestone are frequent. In the upper part is a band of oil-shale ("Kimmeridge Coal"), which can be traced on the same horizon (an horizon swarming with the little stemless crinoid *Saccocoma*) from Kimmeridge on the Dorset Coast to Norfolk, and still further north. In the lower part of the clay *Rhaetorhynchia* [*Rh.*] *inconstans* and *Ostrea deltoidea* are abundant. Higher up the little *Exogyra virgula* occurs in huge numbers, together with *Perisphinctes* [*Ammonites*] *pallasianus*. Remains of huge reptiles (*Ichthyosaurus, Plesiosaurus* and *Pliosaurus*) are common. In the South of England the Kimmeridge Clay passes up quite gradually into the Portland Sands.

4. Portland Beds (South of England).

The beds can usually be divided into two—

2. Portland Stone Series.
1. Portland Sands.

The Portland Sands are sparingly fossiliferous, they are fine grained, sometimes glauconitic sands, among which occur beds of calcareous sandstone or sandy limestone containing *Cardium portlandicum* and *Trigonia pellati.*

The Portland Stone series is famous for its building stones, though the valuable oolitic freestone does not exceed 20 feet in thickness. Beneath it are limestones with nodules of black chert, and above comes "roach," a limestone full of casts of *Aptyxiella* [*Cerithium*] *portlandica* and *Trigonia gibbosa.*

Towards the north, *i.e.*, towards the area of uplift in Central England, there is evidence of an unconformity between the upper and lower divisions of the Portlandian, a conglomerate of lydite pebbles occurring at the base of the upper series (especially at Swindon). At Aylesbury the Portland Sands are replaced by a clay—the Hartwell Clay. The upper beds disappear a few miles to the north-west of Aylesbury. Ammonites reach an enormous size in the Portland Stone—especially *Trophonites pseudogigas* and *Gigantites giganteus.*

5. Purbeck Beds.

This group is magnificently developed in the so-called "Isle" of Purbeck, and falls into three divisions—

Upper—freshwater.
Middle—freshwater and terrestrial with marine bands.
Lower—freshwater and terrestrial.

The whole series usually rests conformably on the Portlandian, but has a more restricted distribution, and passes up without a break into the Wealden. There are, however, local non-sequences and breaks in the series itself.

LOWER PURBECK BEDS. At the base is a "dirt-bed" or ancient soil with stumps of fossil cycads, resting directly on Portland Limestone. This is followed by a series of marls and limestones, with ostracods (*Cypris purbeckensis*) and the freshwater gastropod *Planorbis fisheri*. Several dirt-beds occur locally. Where the basal dirt-bed is absent Purbeck and Portland Limestones may be united in a single block.

MIDDLE PURBECK BEDS. These comprise—

Dark shales with fibrous calcite or "beef" (Beef Beds).
Second Marine Band (*Corbula alata*).
Freshwater Limestones (Upper Building Stones).
First Marine Band ("Cinder Bed"—*Ostrea distorta*).
Freshwater Limestones (Lower Building Stones).
Dirt Bed with Mammalian remains.

A most interesting series of 24 small mammals has been found in the basal dirt-bed at Durlston Bay. The essentially Jurassic Echinoid *Hemicidaris* has been recorded from the Cinder Bed.

UPPER PURBECK BEDS. These freshwater limestones, with *Unio valdensis*, *Cypridea punctata* and *Viviparus cariniferus* yield the famous green Purbeck Marble or Paludina Limestone.

To the north the Purbeck Beds are thinner in the Vale of Wardour, but are quite typical; at Swindon they rest unconformably on the Portlandian, though the relations are very puzzling; a little to the north of Aylesbury they die out. Upper Purbeck Beds are the lowest strata exposed in the Wealden anticline and gypsum deposits occur there.

FIG. 56. Map showing the Cretaceous-Jurassic Unconformity in South-Eastern England. The line of large diamonds is the axis of uplift which became operative in Upper Jurassic times. The Kimmeridge Clay is thin over this axis, which also separates the two Portlandian provinces and along which the unconformity at the base of the Cretaceous is very marked. The obliquely ruled area is roughly that over which the Jurassic is absent and Cretaceous Rocks rest directly on Palæozoic. Smaller axes of folding in pre-Cretaceous times are also shown. It should be noted that they are "Charnian" in trend. Some of these axes were operative as late as the Tertiary (*e.g.*, N. Essex and Suffolk). (*L.D.S.*) Two important papers should be studied in connection with the underground structure of south-east England—R. H. Rastall, on the Tectonics of the Southern Midlands, *Geol. Mag.*, vol. lxii., 1925, pp. 193-222, and R. H. Rastall, The Underground Structure of Eastern England, *Ibid.*, vol. lxiv., 1927, pp. 10-26. The intensive campaign of boring for oil, especially during the Second World War, led to many discoveries. See G. M. Lees and A. H. Taitt, *Quart. Jour. Geol. Soc.*, vol. ci., 1946, pp. 255-317, and P. E. Kent, *Proc. Geol. Assoc.*, vol. lx., 1949, pp. 87-103.

6. Wealden Beds (usually classed as Cretaceous).

Both the fauna and flora of these old lake deposits have strongly marked Jurassic affinities, the beds themselves pass down gradually into Purbeck Beds, but are succeeded, with a slight unconformity by the marine clays of the Atherfield Clay.

The strata were laid down in a great lagoon, stretching from the borders of Devon and Dorset on the west to the Boulonnais on the east, and with an unknown extension to the south in France.

A little outlier of ferruginous sandstone, resting on Portlandian, at Shotover Hill, near Oxford, may be Purbeckian or Wealden.

The beds fall into a lower series—largely sandy—and an upper series—largely clayey—but further more local divisions can be distinguished at least in the Weald of Kent—

Wealden	Weald Clay	
	Hastings Sand Group	Tunbridge Wells Sand.
		Wadhurst Clay.
		Ashdown Sands with (locally) Fairlight Clay at the base.

The Wealden Beds are thickest in the centre of the English portion of the lake, and thin away in all directions (see *Fig.* 57).

The Ashdown Sands are chiefly remarkable for the plant remains found in the Fairlight Clay near Hastings. The Wadhurst Clay has bands of freshwater limestone — formed of the shells of *Cyrena media* and *Viviparus fluviorum* (Sussex and Bethersden Marbles), and also beds of fossiliferous calcareous sandstone (Tilgate Stone). From the latter have been obtained a series of reptilian remains—*Iguanodon mantelli*, *Hylæosaurus oweni* and *Lepidotus mantelli*. *Estheria* occurs in the main mass of the Wadhurst Clay. Towards the base of the Wadhurst Clay occur nodules and seams of clay-ironstone. These were the source of the iron which made the Weald of Sussex famous as an iron-smelting district in the Middle Ages.

The Tunbridge Wells Sand is unfossiliferous, and chiefly remarkable from the way in which it weathers into great rounded rocks—due to irregular impregnation by a ferruginous cement.

The Weald Clay comprises shales and clays, with one or two thin bands of *Paludina* Limestone (*Viviparus fluviorum* and *V. sussexiensis*), and resembles the Wadhurst Clay. Further west these divisions cannot be recognized. The upper part of the Wealden only is exposed in the Isle of Wight. The "Pine

FIG. 57. The Wealden "Lake." Existing outcrops are dotted; original Wealden land is indicated by oblique lines. (*L.D.S.*) See also S. W. Wooldridge and F. Goldring "The Weald," *Collins*, London, 1953.

Raft," on the western coast of the Isle, is a mass of drifted trunks of conifers. Both towards the western end of the lake and the eastern the sands become coarser—even conglomeratic—but thinner. On the coast of Boulonnais, near Wimereux, a coarse conglomerate fills a channel in Purbeck Beds, and may therefore be of Wealden Age. Towards the north-western shore of the lake, in the Vale of Wardour, the lower beds of the Wealden are absent, and the upper rest unconformably on the Purbeck.

B. Scotland.

The Upper Jurassic Strata of Scotland occur on the West Coast and on the East Coast in the north. The most complete succession is found on the East Coast. The Brora Coal (Bradfordian) is followed by a representative of the Kellaways Rock, followed by lower Oxfordian Clays, but evidence of a shallowing of the sea is not lacking, and estuarine conditions set in. They have left a great thickness of sandstones, with some seams of coal and some marine intercalations. These are succeeded by alternating marine and Estuarine Beds of Kimmeridge age. Among them are beds of very coarse angular breccia, which would seem to be due to occasional but violent floods, perhaps assisted by river ice. The highest beds are unfossiliferous estuarine sands.

It would seem that the main Jurassic land lay to the north, and that the Estuarine Beds were deposited by a huge river draining southwards and emptying into an arm of the sea which extended up to the West Coast of Scotland and along the line of the Great Glen.

ECONOMIC GEOLOGY OF THE UPPER JURASSIC.

1. **Lime and Cement.** Not very important.
2. **Building Stones.** Very important.

a. Corallian. The Coral Rag and Coralline Oolite have been much quarried near Oxford (especially at Headington), and the stone is used in many of the Oxford Colleges. The stone usually consists of a mass of comminuted shells, and weathers badly unless placed in the same way as originally taken from the quarry, *i.e.*, with the bedding horizontal.

b. Portland. The fine Portland Oolite has already been mentioned. It may be shelly or practically free from fossils. It has been used in many famous buildings—St. Paul's Cathedral, British Museum and King's College, London. The "roach"—very vesicular owing to dissolution of fossils—is very little used.

c. Purbeck. Some of the shelly limestones are used for building, but of more importance is the famous Purbeck Marble, used especially for interior work, as in the Temple Church, London.

d. Wealden. Some bands of freshwater limestone — largely made up of the shells of *Paludina*—resemble the Purbeck Marble, and are used for similar work. They lack, however, the beautiful green colour of the Purbeck stone. They are known as the Bethersden and Sussex Marbles.

The famous Caen Stone of Normandy is Upper Jurassic.

3. Road Stone. Not very important. Various stones are used locally, especially the Corallian.

4. Sands. The Kellaways Rock of Yorkshire has yielded a little moulding sand; the Wealden Sands (Ashdown and Tunbridge Wells Sands) yield important supplies of pure sand, as yet little exploited.

5. Clays. Important.

a. Oxford Clay. There is a marked tendency for the brick-making industry to become concentrated in certain localities where material is good and transport is easy. One of these centres is Peterborough—perhaps the greatest brick-making centre in the world. The raw material used is Oxford Clay, and the articles made are generally red, though they can be made "white." The Oxford Clay is also used elsewhere—as at Oxford.

b. Some Corallian Clays and Kimmeridge Clay are also used

c. The Wealden Clays are used for bricks, but the clays suffer from too large a quantity of iron salts or calcium sulphate.

6. Iron Ores.

a. Corallian. The millet-seed iron ores of the Kent Coalfield are apparently of this age; also Westbury and Abbotsbury ores.

b. Wealden. Formerly important in Kent and Sussex.

7. Oil Shale. The story of the exploitation of the well-known Kimmeridge Coal or Oil Shale is one of a succession of failures. It has been known to yield as much as 75 gallons to the ton of shale, but the high content of sulphur caused a very offensive smell, and attempts to eliminate that element have so far resulted in the destructive distillation of the paraffins and the crude oil loses its value.

8. Water. Very few important towns are situated on Oxford or Kimmeridge Clays unless they have a covering of gravel. Portland Stone yields a good supply, but its outcrop is too limited.

9. Scenery and Agriculture. The Upper Jurassic Clays give rise to some of the largest areas of flat, low-lying ground in England. They underlie the flats of Cambridgeshire and practically the whole of Fenland. The harder beds stand out as but moderately marked escarpments. Some interesting examples of coast scenery are afforded by the almost vertical Upper Jurassic and Cretaceous beds of the Isle of Purbeck. Breaking through the wall of hard Purbeck limestone, the sea hollows out a great bay in

the soft Wealden and Lower Cretaceous beds behind, producing a narrow necked gulf, such as Lulworth Cove.

FOREIGN JURASSIC STRATA.

Geography of the Period.

The history of Europe is really a repetition on a larger scale of the history of England. An ocean from the south overflowed the Triassic lakes of Germany. The earlier rocks belong to the Rhætic Period; both the Rhætic and Lias are local in their distribution. Then followed an enormous marine transgression—perhaps the greatest known in geological history — culminating in Oxfordian times. Then, in Upper Jurassic (post Oxfordian) times, there was a partial retreat of the sea giving rise to lagoons in the Purbeck and lakes in the Wealden. The sea remained, however, in the Alpine or Mediterranean province, and is known as the Tithonian Sea. In it was deposited the Tithonian type of Portlandian.

Classification.

The foreign Jurassic falls into three types or provinces, *i.e.*, provinces which are really types.

a. Alpine, Mediterranean or Equatorial Type. Occurs in the Alps, Carpathians, the peninsulas of Iberia, Italy, Balkans and Crimea, Inner Caucasus, Further India, Central Africa and Mexico—*i.e.*, from 30° N. to 30° S. Characterized by the abundance of the *diphya* type of *Terebratula* (*Pygope*) and by the great richness in ammonites of the genera *Phylloceras, Lytoceras, Haploceras* and *Simoceras*.

There are various facies—

(i.) red Ammonite-bearing marbles, very like the Triassic Halstatt Marble, at various horizons;

(ii.) white or reddish limestones often with breccias—many brachiopods and crinoids;

(iii.) uniform calcareous shales—Aptychus Shales.

The bulk of the Alpine Jurassic is Lias and certain parts of the Upper Jurassic. The Middle Jurassic is poorly developed and also poor in fossils. The lower part of the Upper Jurassic is well developed and has coral reefs. Succeeding beds which have been correlated with the Kimmeridge Clay are the great *Diphya* Limestones (white or reddish marble). These are succeeded by an Ammonite Limestone, and the two constitute the Tithonian of Oppel, which passes gradually upwards into the Cretaceous.

b. Middle European Type. Occurs in France, Germany, England, North-Western Spain, and again in the Southern Hemisphere in New Zealand, Australia, Cape Colony, Argentine, etc. *Phylloceras* and *Lytoceras* are rare, but *Peltoceras* and *Aspidoceras* become important. Coral reefs of considerable extent and thickness occur.

The development of the Jurassic in France and Germany closely resembles that in England.

c. Russian or Boreal Type. Occurs all round the North Pole in Northern Europe and Northern Asia. The Lias and lower part of the Middle Jurassic are absent. Generally the lowest beds are Callovian (=Kellaways Rock) or Oxfordian. There is a great development of *Cardioceras;* most of the Alpine types of ammonites are absent, reef-building corals are also conspicuous by their absence. The lamellibranch *Aucella* is abundant.

On this evidence Neumayr concluded that climatic zones had been established on the earth in Jurassic times. The recurrence of Middle European types in the Southern Hemisphere and the absence of corals in the northern regions are certainly suggestive. Neumayr's classification is :—

(1) Equatorial.

(2) Temperate $\begin{cases}\text{cold.}\\ \text{warm.}\end{cases}$

(3) Boreal.

More recently, some authors prefer to distinguish only two "provinces"—Equatorial and Boreal. Cold and warm currents existed as at the present day, and the warm-water forms—possibly pelagic swimmers—such as *Phylloceras* and *Lytoceras* were carried by currents as far north as Alaska. It has been suggested also that many of the "boreal" types were restricted to Continental shelves, and that their distribution was controlled by the configuration of the Continents.[1]

LIFE OF THE PERIOD.

In the faunas of the Jurassic Lamellibranchs and Gastropods share the supremacy in point of numbers with Ammonites. The latter, from their specialized and short-lived variations, are particularly valuable as zonal indices. Echinoids, Brachiopods and Reptiles are other important members of the Jurassic faunas.

a. Plants. Cycads are very important (*Zamites, Nilssonia, Williamsonia*, etc.), ferns are also common, and Conifers.

b. Vertebrata. Perhaps the most distinctive members of the Jurassic faunas are the giant reptiles. The Dinosaurs were land animals—often of gigantic size up to 70 or 80 feet long—some walked on two legs like Kangaroos (*Iguanodon* in the Wealden). The Pterosaurs (Pterodactyles) were adapted for flight, the Ichthyosaurians (*Ichthyosaurus*) and Sauropterygians for life in the sea. The earliest bird, *Archæopteryx*, with strong reptilian affinities, is Jurassic. Various small egg-laying or pouched mammals occur, but only rarely.

c. Mollusca. Lamellibranchs are abundant, especially *Trigonia, Ostrea* and *Pholadomya*, and also Gastropods, amongst

[1] The author is indebted to Dr. L. F. Spath for some suggestions in this section.

which the curious *Nerinea* may be noted. Amongst Cephalopods, the Nautiloids are represented almost exclusively by *Nautilus*, whilst the Ammonoids are extraordinarily abundant. On the whole, keeled Ammonites tend to occur in the Lower Jurassic, unkeeled in higher beds. Belemnites are also abundant.

d. Brachiopoda. There are a few Palæozoic survivals, notably of the spire-bearers—*Spiriferina* in the Lias, but the majority of the Jurassic species belong to the loop-bearers — *Terebratula, Terebratella* or *Rhynchonella.*

e. Echinodermata. Crinoids are locally common, but Echinoids are the predominant Mesozoic Echinodermata. The Cidaroids (*Cidaris*) and Diademoids (*Acrosalenia* and *Hemicidaris*) amongst the regular orders, and amongst the irregular forms *Pygaster, Holectypus, Nucleolites* and *Clypeus* may be especially mentioned.

f. Cœlenterata. Most of the Jurassic corals are Hexacoralla, and most of the known families originated in the Trias or early Jurassic. Important examples are *Montlivaltia, Isastræa* and *Thecosmilia.*

g. Protozoa. Foraminifera may be washed out of most Jurassic clays.

CHAPTER XV.

THE CRETACEOUS SYSTEM.

NAME. From Creta (Latin) = Chalk. Chalk is the dominant formation in the upper part of the Cretaceous.

CLASSIFICATION.

	Northern Area.	Southern Area.
Upper[1] Cretaceous	Upper Chalk = Senonian.	
	Middle Chalk = Turonian.	
	Lower Chalk = Cenomanian.	
	Red Chalk.	Gault.
Lower Cretaceous		Lower Greensand.
	Speeton Clay, etc.	
		Wealden.
		Purbeck.
		Portland.
Jurassic	Kimmeridge Clay.	Kimmeridge Clay.

GEOGRAPHY OF THE PERIOD.

1. We have already seen that at the end of Jurassic times the greater part of England was land with a large lake or lagoon—the Wealden Lake, in the south-east.

2. Cretaceous times opened with a marine invasion of this land. The transgression took place

a. from the north,
b. from the south,

against a central ridge.

The movement of waters from the north took place earlier than in the south, so that, from strict chronology, the earliest deposits there (lower part of the Speeton Clay) should be considered as Jurassic.

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[1] By Continental geologists the Gault is usually placed in the Lower Cretaceous, but it is far more convenient to follow the English usage and consider it as Upper Cretaceous. The Wealden is usually classed as Lower Cretaceous.

3. In early Cretaceous times, then, there were two areas of deposition in which the deposits and faunas are very different. The species of Ammonites which characterize the northern province are mostly species well known in Russia.

4. The main ridge against which the two seas battled from the north and from the south seems to have stretched from Charnwood Forest through Bedfordshire in a south-easterly direction under London, and thence along a more easterly course into Belgium.

We have seen that a ridge was forming in approximately this position during the latter part of Jurassic times, and later movements seem to have had a definitely Charnian trend (N.W.—S.E.) (" posthumous Charnian folding ") (see *Fig.* 56).

5. Temporary connexion was established across the ridge in Lower Greensand times. Deposits of this age are mostly sands resting, probably, in erosion hollows, since they vary rapidly in thickness, and have a discontinuous outcrop.

6. Permanent connexion was probably not established till somewhat later, since the lithology and faunas of the two areas continue to be very different until the Lower Chalk.

7. In Bedfordshire the Lower Greensand rests unconformably on Oxford Clay (*Fig.* 56). The further one goes to the south-east the greater is the unconformity. Under London Gault rests directly on Palæozoic rocks, whilst in Belgium the ridge was not covered until the end of the Chalk period (*Fig.* 58).

8. After Lower Greensand times the history of the Cretaceous is that of a great marine transgression all over the north-west of Europe. This movement is frequently referred to as the " Cenomanian Transgression," though it commenced much earlier.

9. The lands invaded were relatively low, and yielded little sediment. There had been no great earth-movements to build up mountain chains or high land since the Carbo-Permian epoch. The pure soft limestone known as the Chalk stretches from Ireland to Russia almost without change. Yet we know its coastline was

FIG. 58. Section across the old Palæozoic Ridge under London. Some of the more important deep borings are indicated:—I, Penshurst; II, Streatham Common; III, Tottenham Court Road; IV, Kentish Town; V, Turnford; VI, Ware. Tertiary Rocks are shown above the Chalk; below it are Gault (solid black) and Lower Greensand (dotted). The folding in the Palæozoic Rocks is hypothetical. Vertical Scal 1 inch = 4,000 feet; length of section about 70 miles. (*L.D.S.*)
A more detailed section across the London Syncline is given in *Fig.* 69.

not far away — coastal deposits are known in Scotland and Austria. It is true also that the percentage of terrigenous (clayey) material increases steadily from Kent to Devon. In Belgium shallow-water sands represent the lower Chalk. The Chalk, despite its similarity to the present-day deep-sea Globigerina ooze, was formed in clear but not necessarily very deep water. Professor E. B. Bailey (*Geol. Mag.*, vol. lxi., 1924, p. 102-116) has concluded that the Chalk-sea was bordered by a matured hot desert, corresponding in type with the Sahara of to-day and that lack of rain on the neighbouring land was one main reason for the sea's abnormal purity.

10. The approximate limits of the Cretaceous Sea at different periods of the transgression are shown in the sketch map (*Fig.* 59).

11. The sea was deeper in Turonian times, but its greatest extent was probably in lower Senonian times. Upper Senonian times were marked by a re-

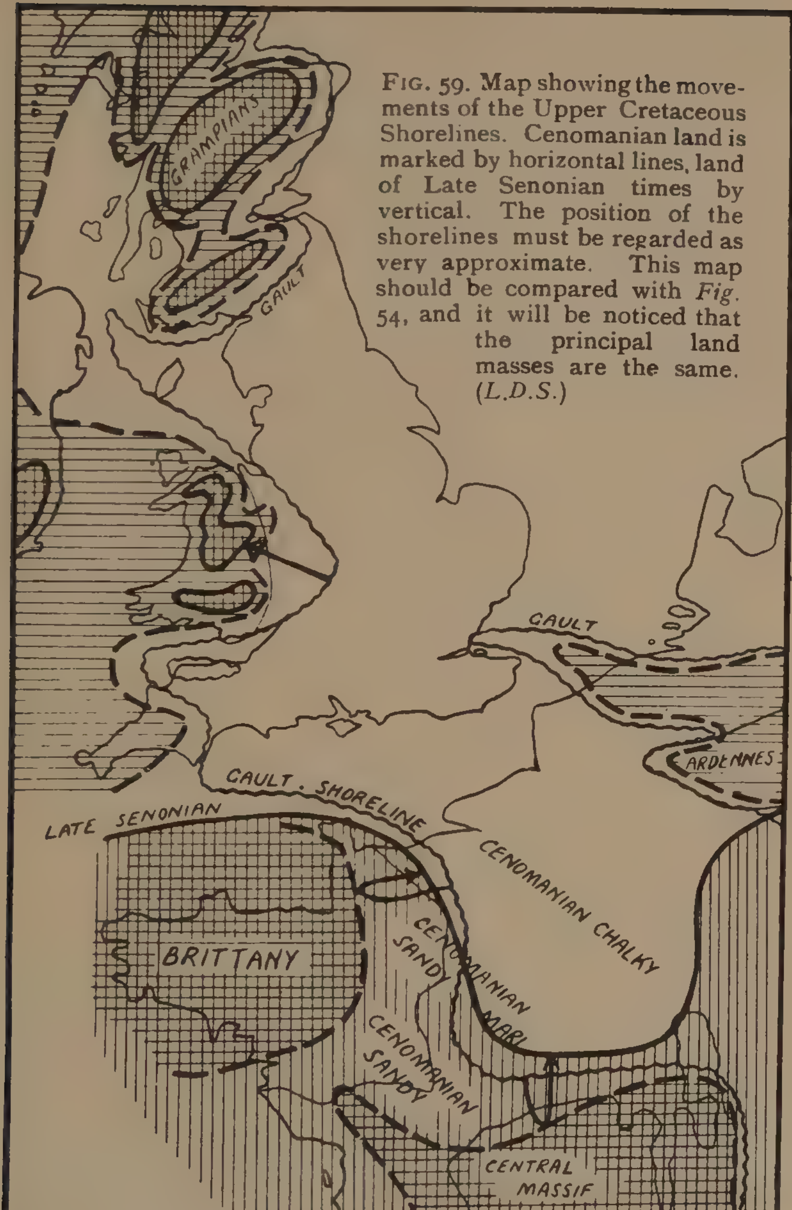

FIG. 59. Map showing the movements of the Upper Cretaceous Shorelines. Cenomanian land is marked by horizontal lines, land of Late Senonian times by vertical. The position of the shorelines must be regarded as very approximate. This map should be compared with *Fig.* 54, and it will be noticed that the principal land masses are the same. (*L.D.S.*)

NOTE.— The hill top surface in North Wales, as well as the plateau surface of Devon and Cornwall, may be due to submarine planation by the Upper Chalk Sea.

treat in the south (France), though this is not noticeable in England, where its greatest extent was later in the Senonian period.

12. There is evidence of temporary shallow-water periods during the deposition of the chalk (marked by Chalkrock with its gastropod fauna).

13. The geography and history of the period between the deposition of the highest chalk in England and the lowest Eocene is detailed later.

LOWER CRETACEOUS IN ENGLAND.[1]

A. SOUTHERN PROVINCE.

If one excludes the Wealden, the Lower Cretaceous comprises simply the " Lower Greensand Formation " or Aptian (or Vectian). Very little is known concerning the detailed palæontological zoning of the Aptian, and at present the whole division is often quoted as the " zone " of *Parahoplitoides deshayesi,* a fossil that is certainly characteristic of a certain part. The principal areas in which the Lower Greensand crops out are inside the Chalk escarpments of the Weald, in the Isle of Wight and in Dorsetshire.

1. Wealden Outcrop.

Typically developed in the neighbourhood of Folkestone,[2] the succession being :—

4. Folkestone Beds, light greenish sands, with irregular beds and masses of calcareous sandstone.
3. Sandgate Beds, glauconitic clays.
2. Hythe Beds, glauconitic sandstones and limestones, with *Exogyra sinuata* and *Terebratula sella.*
1. Atherfield Clay, with *Perna mulleti.*

When traced inland the only constant bed is the Atherfield Clay, which is found all over the southern province from Dorsetshire to Kent. It is, however, rarely exposed in the Weald. The invasion of the Wealden lake by the sea must have been a very gentle one. When the junction can be seen—it was admirably displayed in some cores from coal explorations in East Kent—the upper

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[1] A. J. Jukes-Browne, " The Cretaceous Rocks of Britain," *Mem. Geol. Surv.* (1900-1904), Vols. I.-III.

[2] It should be noted that " Lower Greensand," as applied to the whole formation, is very inappropriate.

part of the Weald Clay is often seen to be bored by molluscs and the borings—in which the shells sometimes remain—are filled with Atherfield Clay. There is a colour difference between the two clays.

Traced northwards from Folkestone the Lower Greensand rapidly thins out against the Palæozoic ridge, and under Herne Bay Gault rests directly on Palæozoic. Westwards the Hythe Beds are the most important of the three upper divisions, as they include thick beds of massive or porous glauconitic sandy limestone (Kentish Rag), which is much quarried for road-metal and building stone near Maidstone. Elsewhere the Hythe Beds are represented by unfossiliferous ferruginous sands and cherts—occasionally with pebbles of Palæozoic rocks Away from the type locality Sandgate Beds cannot really be separated from the Hythe Beds. In Surrey, at Tilburstow Hill, near Godstone, there are thick beds of chert at about this horizon, two miles further west at Nutfield valuable beds of Fuller's earth occur in the midst of glauconitic marly sandstones (with *Panopæa plicata* and *Parahoplitoides deshayesi*). The Folkestone Beds are mainly red and white unfossiliferous sands, sometimes with hard bands (Bargate Stone) or cherts. Across the Channel, near Cape Blanc Nez, the whole of the Vectian is represented by 20 or 30 feet of marine clays. The shoreline cannot have been much farther to the east.

2. Isle of Wight.

The Atherfield Clay is well seen, and very fossiliferous. The Basement Bed is really a " bone-bed "—fragments of bones, probably of Wealden fish, are mixed with small pebbles—in fact, just such an accumulation as one would expect from the invasion of a lake by marine waters (compare Rhætic Bone-Bed). At the base is the hard very fossiliferous bed called the " Perna-Bed " from the abundance of *Perna mulleti*. At the top of the clay is another hard bed (the " Crackers ") with *Parahoplitoides deshayesi*, *Panopæa plicata* and *Gervillea sublanceolata*. The beds above the clay are mostly sands, with numerous fossil bands (*Exogyra sinuata*, *Meyeria vectensis*, *Terebratula sella*). The highest bed of the sandy series is a

ferruginous sand-rock known as the Carstone—the higher part at least is probably equivalent to the lowest bed of the Gault.

3. Dorsetshire.

The Atherfield Clay—here considerably thinner—is succeeded by a series of ferruginous or white sands.

To the north, in the Vale of Wardour (Wiltshire), the Vectian, only about 50 feet in thickness, overlaps the Wealden, and is itself overlapped by the Gault. The beds here may represent the Hythe Beds of Kent.

The distribution and variation in thickness of the Lower Greensand deposits raise several interesting points.

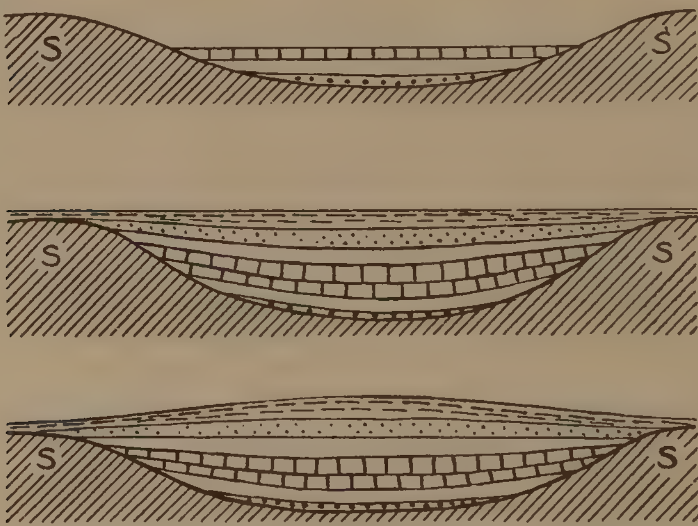

FIG. 60. Diagram to illustrate the formation of a superficial anticline superimposed on a syncline. S S are relatively stable blocks: the intervening area is supposed to be capable of being pressed down by the weight of strata deposited on it. (*L.D.S.*)

a. The deposits cover practically the same area as the Wealden lake.

b. From a centre — somewhere about the western end of the Weald—they thin away in all directions, that is, they thin away from the centre of

the basin of deposition. This may be partly due to earth-movements and pre-Gault erosion, but is mainly original.

c. Why should the centre of a basin of deposition have the greatest thickness of deposit?

d. It seems to be quite possible that the weight of sediment pushes down the sea floor more and more. The western end of the Weald seems to have been weighted down in this way during most of Jurassic and in early Cretaceous time. The underlying Jurassic sediments here reach an enormous thickness—the Kimmeridge Clay alone being 1,250 feet.

e. In this way an ever-deepening syncline between two relatively stable areas results.

f. At last there is a gradual reversal, and the syncline gradually rises and becomes an anticline, which, by reason of the thickness of the beds, is a superficial anticline superimposed on a syncline (as shown in *Fig.* 60).

Such is believed to be the structure of the Weald.

B. LOWER GREENSAND IN THE MIDLANDS.

So little is known of the exact relationships of the various patches of sands, etc., in the Midlands that they may be mentioned here separately.

1. Seend, Wiltshire. Ferruginous sands have been worked for iron-ore.

2. Faringdon, Berkshire. Here, resting on Kimmeridge Clay, are beds of sand and "gravel." The latter includes many rolled Jurassic fossils, but consists very largely of contemporary calcareous sponges—*Raphidonema faringdonense, Barroisia anastomans*—together with brachiopods—*Terebratella menardi* and *Rhynchonella latissima* — and echinoderms — *Peltastes wrighti*—and also *Belemnites speetonensis*. Elsewhere in North Wiltshire and Berkshire, sands with bands of pebbles are found.

3. Buckinghamshire and Oxfordshire—patches of sands of varying thickness rest unconformably on Purbeck, Portland or Kimmeridge Beds.

4. Bedfordshire. The Woburn Sands suddenly attain a considerable thickness — 250 feet—and include valuable deposits of Fuller's earth. The sands are generally unfossiliferous, but the Faringdon Fauna has been found near the base. At the base is a bed with phosphatized Jurassic fossils. The " Brachiopod Limestone " of Leighton Buzzard will be mentioned under the Gault. The other pebbles in the Basement Bed suggest a derivation from the old Palæozoic Land—forming the ridge under London—to the south-east.

5. From Bedfordshire to Norfolk and Lincolnshire. Similar sands, often with a bed of phosphatic nodules and rolled Jurassic fossils at the base, have an almost continuous outcrop. In Norfolk the marine Snettisham Clay becomes intercalated between sands below and ferruginous sandstone (" Carstone ") above.

C. NORTHERN PROVINCE.

1. Yorkshire.

Here the Speeton Clay is believed to bridge over a great part of the gap between the Kimmeridge Clay and the Lower Chalk. An exact correlation is difficult with the beds in the South of England, as the fossils are so entirely different, and can only be compared with those in Russia.

The succession at Speeton Cliff is :—

7. Red Chalk.
6. Clays and marls, with *Belemnites minimus*.
5. Clays and " Cement-beds," with *Belemnites brunsvicensis, Parahoplitoides deshayesi, Exogyra sinuata.*
4. Clays, with *Belemnites jaculum, Exogyra sinuata* and *Terebratula sella.*
3. Compound nodular bed, with phosphatic casts of Ammonites of the *Hoplites* type.
2. Clays, with *Belemnites lateralis.*
1. Coprolite-Bed (phosphatic nodules), with phosphatic casts of the Portlandian ammonite, *Olcostephanus.*

Bed 2 is generally correlated with the Purbeck Stage. If the phosphatized fossils in Bed 1 are regarded as contemporary, then this bed may represent the greater part of the Portlandian — it rests on Kimmeridge Clay — which

was here a period of non-deposition. If, on the other hand, they are regarded as derived, then this "Coprolite-Bed" merely becomes a basal bed of 2.

Bed 3 is usually taken as the base of the Cretaceous in Yorkshire, as the ammonite genus *Hoplites* is a Cretaceous one.

Bed 4 is usually correlated with Neocomian—*i.e.*, with the marine beds in France of the same age as our Wealden. Its fossils do not mark it off very clearly from the Aptian deposits.

Bed 5 is certainly the equivalent of the Aptian or Vectian.

Bed 6 corresponds to the lower part of the Gault. It is a transition bed to the Red Chalk (=upper part of Gault).

2. Lincolnshire.

Naturally, traced southwards towards the land ridge, the Speeton Clays pass into sandstones. The succession in Lincolnshire is:—

Red Chalk, with carstone at the base = Gault.
Tealby Limestone passing southward into Roach Ironstone = Lower Greensand.
Tealby Clay } = Neocomian.
Claxby Ironstone }
Spilsby Sandstone = Purbeck.

The Spilsby Sandstone has a basal bed of phosphatic nodules, and it yields *Belemnites lateralis* and *Aucella*.

The lower part of the very fossiliferous Claxby Ironstone (formerly worked as an Iron-ore) also yields *Belemnites lateralis*, but *B. jaculum* occurs in the higher part. To have the base of the Neocomian on the same horizon as in Yorkshire, it is necessary to draw the line somewhere in the Ironstone. Lamellibranchs are abundant, especially *Arca*, *Exogyra sinuata* and *Trigonia ingens*. It is an earthy oolitic ironstone.

The Tealby Clay is rarely exposed, but yields *Belemnites jaculum*, *Exogyra sinuata* and *Perna mulleti*.

The Tealby Limestone (passing southwards into clay and ironstone) yields *Belemnites brunsvicensis* and *Exogyra sinuata*.

The more exact zoning of the Speeton Clay has been based chiefly on the species and varieties of the Russian ammonite genus *Simbirskites* and allied genera.

UPPER CRETACEOUS IN ENGLAND.[1]

In Upper Cretaceous times the two areas of deposition were definitely united, although a great difference exists between the deposits at first laid down in the south (Gault Clay) and in the north (Red Chalk). From a comparison with the zones in the South of France there is probably a small break between the Folkestone Beds and the lowest zone of the Gault. The lowest Gault sometimes rests with a slight unconformity on the underlying Lower Greensand deposits, especially round the edge of the basin of deposition of the former, and the Gault overlaps to a very considerable extent in all directions. More detailed investigation seems to show that the Lower Greensand was thrown into a series of east and west folds before the deposition of the Gault. This is particularly well seen in Dorset and Wiltshire.

THE GAULT.

Five zones may be distinguished. They are :—

5. Zone of *Pecten asper*.
4. Zone of *Pervinquieria* [*Am.*] *rostrata*.
3. Zone of *Hoplites lautus*.
2. Zone of *Hoplites interruptus*.
1. Zone of *Douvilléiceras mammillatum*.

The value of the highest zone is very doubtful. It is frequently taken as the basal zone of the Chalk. *Pecten asper* is, in reality, a facies fossil, and is associated with shallow water sandy conditions. In Belgium it is found in such deposits at a higher horizon. *Cardiaster fossarius* is, perhaps, a better zone fossil. Many local names have been given to the various lithological types occurring on the horizon of the Gault. In particular a sandy facies of the upper part is known as the "Upper Greensand."

The variation in lithology is very easily understood by means of diagrammatic sections (*Figs.* 61 and 62), one drawn from west to east (Devon to N. France), the other from south to north (Devon to Yorkshire). In these

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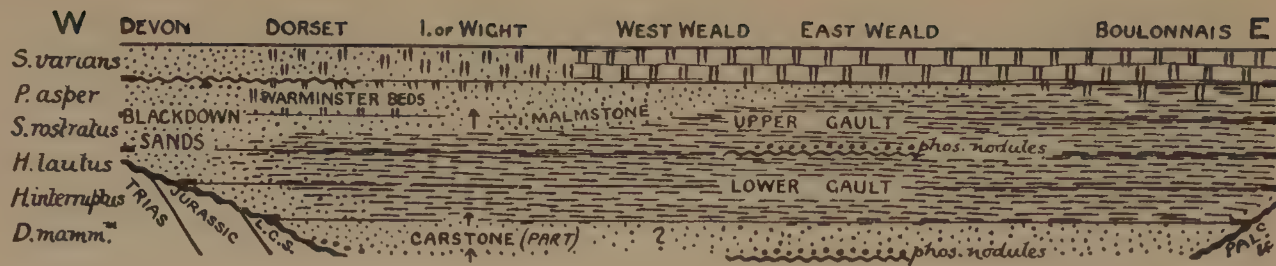
[1] The Cretaceous Rocks of Britain, vols. i.-iii., *Mem. Geol.* see also the series of papers by A. W. Rowe and later by C. T. A. Gaster in the Proceedings of the Geologists' Association.



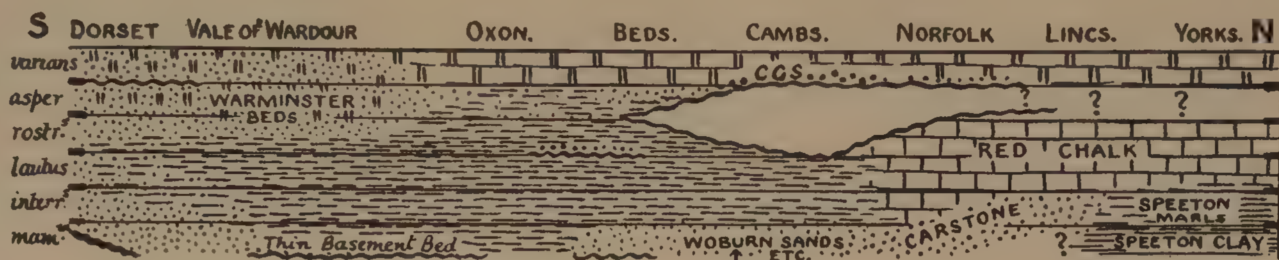


FIG. 61. Diagrammatic Section showing the lithological variation of the Albian (Gault) of England from West to East.

FIG. 62. A similar Section from South to North. Horizontal Scale roughly 50 miles to one inch. (*L.D.S.*)
[See the important footnote on page 262.]

diagrams no notice has been taken of thickness, the limits between zones has been shown by horizontal lines. It is only necessary to remember that—

a. Sometimes there are slight unconformities at the base of the Gault, at other times there is apparently a gradual passage down into the Lower Greensand. This is largely due to post-Lower Greensand flexuring along east and west lines.

b. The beds become more sandy when traced towards the old shoreline (*e.g.*, in Devon).

c. There is generally a gradual passage upwards, by increase of calcareous material (giving clayey marls, sandy limestones, etc.) into the Chalk.

d. There are local breaks within the Gault itself. The most important of these is in Bedfordshire and Cambridgeshire, *i.e.*, on the crest of the posthumous Charnian fold already mentioned (page 242).

e. The Gault clay of the south is replaced northwards by the Red Chalk.[1]

Notes on the Sections.

The classical exposure of the Gault is at Folkestone. The lowest zone is a grit with phosphatic nodules, and with fairly numerous examples of the zone-fossil. It forms a natural stratigraphical base, although some geologists prefer to place it in the Lower Greensand. The main mass of the Gault Clay has beautiful iridescent fossils and others—pyritized or phosphatized, and more easily removed. The Zone of *Hoplites interruptus* yields the zone fossil in abundance, also *Hamites rotundus*.

The Zone of *H. lautus* yields many species of *Hoplites* (*H. splendens*, *H. tuberculatus*), *Hamites intermedius*, *Turrilites*

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[1] Since the diagrams, *Figs.* 61 and 62 were prepared and the above account written, a paper has been published by Messrs. Kitchin and Pringle (*Geol. Mag.*, April-May, 1922). It would now seem that the Lower Gault (*interruptus* and *lautus* zones of the present account) is far more restricted in its distribution than the Upper Gault. The Lower Gault is probably absent in the western end of the Isle of Wight, in Dorset and in Devon. In many cases in the Midlands it is probably absent also, and the Upper Gault transgresses on to older rocks. The necessary corrections should be made in *Fig.* 61, but sufficient detail is not yet available to correct *Fig.* 62. The position of the Red Chalk of Norfolk is still a matter of dispute. Messrs. Kitchin and Pringle (*Geol. Mag.*, lxix., 1932, pp. 39-40) find it rests *unconformably* on the carstone and passes upward into the Chalk without a break. Dr. R. H. Rastall (*Geol. Mag.*, lxvii., 1930, pp. 456-457) finds there is a gradual transition from the carstone to the Red Chalk, but there is a physical break above the Red Chalk. The red mud is regarded as due to lateritic material derived from a neighbouring land area.

and *Nucula gaultina*. The Zone of *Perv. rostrata*—often known as the Upper Gault—contains *Inoceramus sulcatus*, whilst *Belemnites minimus* and *Nucula pectinata* occur throughout the Gault.

The Zone of *P. asper* is possibly represented by a few feet of sandy beds at Folkestone.

Traced inland the Gault thickens westward; northward it persists, and under London and the extreme northern part of Kent, as well as over a great area north of the Thames, it overlaps the Lower Greensand, and rests directly on Palæozoic strata. Under the North Sea (mouth of the Thames) it is highly probable that the Chalk rests directly on the Palæozoic, just as it does over a great part of Belgium (see *Figs.* 56 and 59).

There is often a break between the "Upper" and "Lower" Gault in Kent, with a layer of phosphatic nodules at the base of the former.

In the Isle of Wight the coarse pebbly sandstone known as the Carstone seems to form the natural base of the Gault.

To the west, in Dorset and Devon, the Gault oversteps on to the Jurassic, and the so-called "Upper Greensand" facies occupies the whole thickness, and the Blackdown Beds in Devon, with their characteristic sponge-spicule chert, represent the whole of the Gault, or at least the upper part. Characteristic fossils are: *Protocardia hillana, Cucullæa glabra, Schlœnbachia varicosa.*

Further north the upper part of the Gault is represented by the Warminster Beds, which, in Wiltshire, pass up gradually into the lowest beds of the Chalk. It will be noticed that the lowest beds of the Chalk rest unconformably on the Gault in Cambridgeshire and Norfolk. At the base of the former is a band of rolled phosphatized fossils and phosphatic nodules, known as the Cambridge Greensand. The fossils include many of the characteristic species of the higher part of the Gault: *Hoplites, Perv. rostrata, Inoceramus*, etc., and also others which are rarely found *in situ* in the Gault of Southern England: *Rhynchonella sulcata, Terebratula biplicata.*

Passing into Norfolk the Gault grades laterally into the Red Chalk — a hard brick-red chalk full of large quartz grains. Fossils include *Belemnites minimus* and *Terebratula biplicata*, and, in the higher part, *Hoplites lautus*, *H. splendens*, etc. The "Carstone" forms the base of the Red Chalk, and possibly represents the Zone of *Douvilléiceras mammillatum*. Passing into Lincolnshire, the same beds are present, but the "Carstone" is on a higher horizon. In Yorkshire the Speeton Marls pass up directly into the Red Chalk.

A very interesting and much disputed problem is presented by the sequence at Shenley Hill, near Leighton Buzzard, Bedfordshire. As an example of a problem it is worth noticing.[1] The apparent sequence is :—

[1] Compare Kitchin and Pringle, *Geol. Mag.*, Jan.-March, 1920, pp. 9-12 and 109-111; and Lamplugh, *Quart. Jour. Geol. Soc.*, vol. lxxviii., 1922, especially p. 80.

Gault Clay.
Conglomeratic bed, with fragments of "Brachiopod Limestone," other fragments, sand, etc., resting with irregular junction on
Woburn Sands (Lower Greensand).

At first sight there is nothing extraordinary in the succession, but, when examined carefully, the fossils in the blocks of limestone are found to be of Lower Chalk (Cenomanian) species. Moreover, in the overlying clay the fossils are such as characterize the Upper Gault (*H. lautus*), but higher up in the clay have been found fossils usually found in the Lower Gault (*H. interruptus*). Two explanations are possible—

(1) Early in Albian times special conditions existed in the neighbourhood suitable for the development of a fauna of Lowest Chalk facies, and which does not appear elsewhere till later—that is the fauna of the "Brachiopod Limestone."
(2) The whole sequence is inverted, a great slab of country having been completely overturned by glacial action so that the conglomeratic bed is really a boulder-clay.

Despite the fossil evidence some weight is added to the first explanation by the occurrence of sandy conglomeratic beds, undoubtedly at the base of the Gault, only a few miles away.

THE CHALK.

Speaking generally, the Chalk is a soft, light-grey to white limestone. It gives rise to the great stretches of white cliff which form the bulwark of England along its south and east coasts. It was formerly divided into Lower, Middle and Upper Chalk, now more exactly defined as Cenomanian, Turonian and Senonian. The Lower or Grey Chalk has a considerable percentage of clayey matter, hence its colour ; the Middle Chalk is purer, but it is the Upper or White Chalk which is most familiar and most characteristic. The grey or black siliceous concretions known as flint are especially characteristic of the lower part of the Upper Chalk. Chalk was formery thought to consist mainly of the remains of tiny foraminifera, and to agree in general characters with the Globigerina Ooze at present being formed in the Atlantic. From the nature of the fossils, however, and from the fact that the Chalk passes laterally into littoral deposits it is unlikely that it was formed in really deep sea, but simply in clear water free from sediment. It is now believed that much of the material is actually a precipitate. The Chalk is magnificently exposed round the English Coasts and in numer-

ous quarries inland. It is extensively quarried for lime-burning and for the manufacture of cement.

GEOGRAPHY OF THE CHALK PERIOD.

This has already been outlined, and is illustrated by the map (*Fig.* 59). Some further details may now be given.

1. The Lower Chalk deposits give evidence of gradual transgression and increase of depth. Pebbles in the Cambridge Greensand at the base in Cambridgeshire show that the old Palæozoic ridge to the south-east was not yet covered, and the Lower Chalk is represented by shallow-water glauconitic sands on the flanks of the ridge in Belgium. Similarly in Devonshire the Lower Chalk is represented by a variable set of calcareous sandstones and sandy limestones; again in Antrim glauconitic sands occur, some containing layers of chert and sometimes calcareous, whilst along the West Coast of Scotland (in Mull, etc.) the Lower Chalk seems to be represented by a series of estuarine beds. In the central region, that is, between these regions of shallow water, the Lower Chalk is divisible into

Hard Grey Chalk,
Totternhoe Stone,
Chalk Marls.

The Chalk Marls have been likened to oozes forming in the Gulf of Mexico. They have a considerable percentage of arenaceous foraminifera which are absent in later and deeper water beds. The Chalk Marl has only 55 to 80 per cent. carbonate of lime, the insoluble residue being clay, fine quartz silt and glauconite.

The Totternhoe Stone is a grey chalk, with a gritty feel, due to shell fragments.

The percentage of carbonate of lime increases in the overlying Grey Chalk to 88 or 95, and silt is almost absent.

2. Middle Chalk times were marked by continued subsidence in France and Southern England, but not in Northern England. In fact, it would seem that there was possibly a regression from the north, as the Middle Chalk

is absent in North-Eastern Ireland and in Scotland, the Upper Chalk resting unconformably on the Lower.

3. At or near the base of the UPPER CHALK is a bed of hard nodular chalk, sometimes with green-coated calcareous or phosphatic nodules. This bed is the Chalk Rock; it has a shallow-water fauna, grains of glauconite and some quartz. The hard nodules were doubtless formed as a result of contemporaneous denudation—change of currents being responsible. This stage was followed by renewed subsidence, and the chalk becomes purer and whiter, and flints become common. In France there was also a shallow-water period on the same horizon as the Chalk Rock, followed by renewed subsidence, but there the Chalk Sea reached its greatest extent in early Senonian times, in England not until late Senonian times. The highest part of our English Chalk has been removed by denudation, but the period of greatest extent of the sea was probably in the zone of *Belemnitella mucronata*. In Antrim and Western Scotland the Lower Chalk is overlain unconformably by glauconitic sands passing up into glauconitic limestones, and then into White Chalk with *Bel. mucronata*. Fragments of chalk dredged up off the Coast of Kerry may indicate that the sea extended as far west as that; but similar blocks from the Moray Firth in Scotland resemble Scandinavian and Danish types, and were probably brought by ice agencies during the Glacial Period.

At the time of the greatest extent of the Chalk Sea the following land probably remained—

a. Brittany.

b. Land to the west of Devon and Cornwall?

c. Parts of Wales. On the other hand, Wales is a denuded peneplane. The peneplane may have been completed by marine denudation under the waters of a late Chalk Sea.

d. Several islands in Ireland.

e. The Southern Uplands?

f. The Central and North-Western Highlands possibly formed peninsulas from some northern land.

g. The Pennine ridge was most likely submerged, as was the old London-Belgium land—the highest Chalk Sea covered even the Ardennes.

CLASSIFICATION OF THE CHALK.

	Zones.	
Senonian[1]	*Ostrea lunata*	Upper Senonian.
	Belemnitella mucronata	
	Actinocamax quadratus	Lower Senonian.
	Marsupites testudinarius	
	Micraster cor-anguinum	
	Micraster cor-testudinarium	
	Holaster planus, with Chalk Rock	
Turonian	*Terebratulina lata.*	
	Rhynchonella cuvieri.	
Cenomanian	*Holaster sub-globosus.*	
	Schlœnbachia varians.	

THE CHALK IN ENGLAND.

1. Zone of *Schlœnbachia varians.* Hard grey fissile marls and hard grey chalk. Flint is typically absent, but beds of flint nodules occur in Wiltshire and Berkshire. At the base the subzone of *Stauronema carteri* (a sponge) is found in the southern counties; it includes some basement beds, especially an arenaceous glauconitic chalk known as the Chloritic Marl. The Cambridge Greensand, already mentioned as being a band of phosphatic nodules and rolled Albian fossils resting on an irregular surface of Gault, also occurs on this horizon. In Devonshire this and the following zones are represented by a quartziferous limestone. Fossils of the *varians* zone: Sponges (*Stauronema* and *Plocoscyphia*), brachiopods (*Cyclothyris* [*Rh.*] *mantelliana* and *C. grasiana*), ammonites (*Schlœnbachia varians, S. coupei, Acanthoceras rhotomagense*) and *Scaphites.*

2. Zone of *Holaster sub-globosus.* Has a more constant lithology, greyish chalk passing up into whiter chalk north of the Thames. The base is marked by a hard gritty chalk — the Totternhoe Stone. Throughout England the highest beds are the Belemnite Marls—grey fissile marls with *Actinocamax plenus.* Fossils: *Holaster sub-globosus*, *H. trecensis*, *Discoidea cylindrica* and *Actinocamax plenus.*

3. Zone of *Rhynchonella cuvieri* or *Inoceramus labiatus.* A hard white or creamy chalk, frequently nodular, with partings of marl. The nodular character becomes accentuated in the lower part, and gives rise to the Melbourn Rock, well marked in the Southern counties. The origin of the nodular character has given rise to much discussion, it is probably due to contemporaneous denudation; a bed of white chalk disturbed soon after its formation, rolled into little pebbles and redeposited in a matrix of more muddy chalk. The sudden variation in thickness of the zone also seem to indicate variable currents. Scattered flints occur in the

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[1] A. W. Rowe, "Zones of the White Chalk of the English Coast," *Proc. Geol. Assoc.*, Vols. xvi.-xx. (1900-1908).

higher part of the zone. Fossils: zone fossils and *Discoidea dixoni*.

4. Zone of *Terebratulina lata*. In the South of England a soft massive white chalk, with few flints, except in Devonshire. The chalk becomes harder and more flinty towards the north. The important fossil genus *Micraster* first appears at this horizon, being represented by the rare *Micraster cor-bovis*. From here, up to the zone of *Marsupites*, the determination of the zone is most easily made by means of the genus *Micraster*. They are common fossils—heart-shaped echinoderms—and each zone has its characteristic form or forms. The gradual evolution of the various species one from another is extremely interesting, and can be easily followed.[1] Fossils: *Conulus subrotundus*, *Ostrea vesicularis* (appears commonly in this zone), *Terebratulina lata*.

5. Zone of *Holaster planus*. This also consists of a hard nodular chalk, except in the northern counties, where it is homogeneous. Flints are common. At or near the base is the Chalk Rock or sub-zone of *Hyphantoceras reussianum*. Where typically developed (as in Berkshire and Oxfordshire) it is a hard cream-coloured limestone, with green phosphatic nodules and grains of glauconite. Elsewhere (as in Kent and Surrey) the fauna is present, but the chalk differs less from the rest of the zone except in being harder and somewhat iron-stained. Contrary to the usual rule in the Chalk, the fossils occur chiefly as casts. Strictly the fauna should be regarded as a facies fauna (shallower-water), and it is not always on exactly the same horizon. Fossils: Numerous lamellibranchs (*Arca*, *Trapezium*), gastropods (*Turbo geinitzi*, *Pleurotomaria*), cephalopods (*Prionocyclus* [*Am.*] *neptuni*, *Scaphites geinitzi*, *Baculites*). The fossils from the remainder of the *H. planus* zone include: Sponges (*Ventriculites*), Echinoderms (*Micraster leskei*, *M. præcursor*, *Holaster planus*, *H. placenta*, *Echinocorys scutatus*), *Terebratula carnea*, *T. semiglobosa*.

This zone is placed by Continental geologists in the Middle Chalk.

6. Zone of *Micraster cor-testudinarium*. A white to yellowish chalk, with nodular layers, especially in the South of England. It is often very fossiliferous: *Micraster præcursor, M. cor-testudinarium, Echinocorys scutatus, Cidaris serrifera, Rhynchonella* spp.

7. Zone of *Micraster cor-anguinum*. A soft, white chalk, with regular bands of flint. Especially well seen in Kent and Surrey, where chalk belonging to this zone forms the great part of the dip slopes of the North Downs. Fossils are only locally common, and include various echinoderms (*Echinoconus conicus*, *Echinocorys scutatus*—large ovate forms—*Cidaris* spp., *Micraster cor-anguinum*), lamellibranchs (*Inoceramus* spp., *Lima hoperi*, *Ostrea* spp.) and brachiopods (*Crania ignabergensis*, *Rhynchonella plicatilis*).

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[1] A. W. Rowe, "Evolution of the Genus *Micraster*," *Quart. Jour. Geol. Soc.*, vol. lv. (1899), pp. 494-545.

8. Zone of *Marsupites testudinarius*. A soft, white chalk, with few flints. Divided into two sub-zones :

b. Sub-zone of *Marsupites*.
a. Sub-zone of *Uintacrinus*.

Phosphatic chalk occurs on this horizon at Taplow. Fossils : Numerous and large specimens of *Porosphæra globularis*, crinoids (*Marsupites*, *Uintacrinus*, *Bourgueticrinus*), belemnites (*Actinocamax verus* lower beds, *A. granulatus* upper beds).

9. Zone of *Actinocamax quadratus* (Southern counties) and *Offaster pilula* (Northern counties). A soft, white chalk, in which flints are more frequent and larger except in Yorkshire. Fossils are not generally abundant.

10. Zone of *Belemnitella mucronata*. A soft, white chalk, with huge flints. Fossils : *Magas pumilis*, *Echinocorys scutatus* var. *pyramidatus*, *Belemnitella mucronata*.

11. Zone of *Ostrea lunata*. Restricted to a small area in Norfolk (Trimingham).

THE CHALK IN SCOTLAND.

Small relics are preserved under the Tertiary lavas of Mull and the adjacent mainland. The beds present are :

White indurated Chalk, glauconitic at base, with *Belemnitella mucronata* (= Upper Senonian).
White sandstones, with seams of coal (= ?Upper Cenomanian)
Glauconitic sands and sandstones, with *Pecten asper* and *Exogyra conica* (= Lower Cenomanian).

The fragments of chalk from Moray Firth have already been mentioned. They also occur in the Pleistocene deposits of Aberdeenshire.

THE CHALK IN IRELAND.

As in Scotland, relics are preserved under Tertiary lavas. The deposits rest on an old early Cretaceous land-surface of Pre-Cambrian, Carboniferous, Triassic or Lower Jurassic strata. The general succession in Antrim is :—

Indurated white Chalk, sometimes with a conglomerate of quartzite pebbles at the base, *Belemnitella mucronata* (= Upper Senonian).
Glauconitic Chalk, with numerous sponges, *Actinocamax quadratus*, *A. verus* (= Lower Senonian).
Yellow glauconitic sands. *Exogyra columba*, *Pecten asper* (= Cenomanian).
Yellow sandstones, *Acanthoceras rhotomagense* (= Cenomanian).
Dark green glauconitic sands. *Exogyra conica*, *Pecten asper* (= Cenomanian, and perhaps part of Albian).

THE CHANGES BETWEEN THE CRETACEOUS AND TERTIARY IN ENGLAND.

The Chalk marks the end of the Mesozoic in England. It is succeeded by the Tertiary. There is a great break in England, although there is not a great or even an obvious unconformity. When seen in a single quarry or cliff face the lowest Tertiary Beds seem to rest quite conformably on the Chalk. Zoning of the latter has shown, however, that the Tertiary may rest on almost any zone of the chalk —especially from *Micraster cor-testudinarium* upwards, showing that enormous thicknesses must have been denuded away. Elsewhere the break between the Cretaceous and Tertiary is less marked; in Belgium there is a fairly complete series of transitional deposits; in the south-eastern Alps and again in Egypt it is difficult to draw a line, and almost impossible in North America.

It is difficult to determine the exact sequence of events at the end of the Cretaceous.

1. A general retreat of the sea. It commenced earlier in France, in fact, before the transgression had reached its height in England. The movement was a gradual one, and little tranquil basins were left (as in France and Belgium), in which chalky strata continued to accumulate.

2. Slight earth-movements took place. These were probably the earliest signs of the great Tertiary movements which culminated in Miocene times. Some post-Cretaceous and pre-Eocene folds are—

a. A gentle uplift of the main Wealden anticline, and probably of the Pewsey anticline.

b. Slight folding along old Charnian lines (N.E. to S.W.)—probably (i.) south of Ipswich, (ii.) Bushey and Willesden through London, (iii.) in East Kent.

c. General uplift in the north and west—the initiation of the great Jurassic and Chalk scarps running across England.

3. Peneplanation of the Chalk surface. This was probably subaerial—partly effected by dissolution of the calcareous material leaving the flints and insoluble matter of the chalk as a curious deposit known as Clay-with-

Flints. Much of the Clay-with-Flints is post-Tertiary, but in some places, especially in Belgium, it is seen to be definitely pre-Eocene.

4. Very gentle invasion by the Eocene Sea.

FOREIGN CRETACEOUS.

Palæogeography.

1. We have already seen that in Triassic, Rhætic and Jurassic times there was a great Southern Ocean, stretching from West to East in approximately the same position as the Mediterranean Sea of the present day, but of much greater extent. As great bays or gulfs opening out to the north of this ocean there were the seas in which the Rhætic and Jurassic deposits of Northern France, England and Germany were laid down. Sometimes arms of these seas were cut off from the main ocean, and became salt lakes, lagoons, or later freshwater lakes (as in Triassic, Purbeckian and Wealden times).

2. Very similar conditions prevailed in Cretaceous times, and, as we shall see later, in early Tertiary times also.

3. Taking the history of France and England, one may say that most of the important geographical units were blocked out in Triassic times, and that they exercised a controlling influence on the area and distribution of Jurassic and Cretaceous seas. Such masses are:

(a) The Massif of Central France.
(b) The Massif of Brittany.
(c) The Massifs of S.W. England and Wales.
(d) The Highlands of Scotland.
(e) The old Palæozoic massif of S.E. England and the Ardennes.

4. In the map (*Fig.* 56) one notices the spread of the Upper Jurassic sea between these old massifs.

5. In Wealden times there were the partially or completely cut off Wealden Lake in the north and the arm of the contemporary sea—in which were deposited the Neocomian strata—stretching northwards as a bay from the Southern Ocean.

6. The Southern Ocean. Following naturally on the "Tithonian" type of Portlandian and Purbeck are the Neocomian strata with *Terebratula diphyoides* in the lower part and further characterized by the oldest Rudistes (a group of curious lamellibranchs). The Cretaceous deposits of this southern ocean are characterised by the presence of large ammonites with free whorls (*Crioceras*, *Ancyloceras*, etc.), as well as by the more normal *Phylloceras* and *Litoceras*. A still more characteristic deposit of this Southern Cretaceous Ocean is the great massive Hippurite Limestone stretching from Southern France through Italy and Greece, and passing into the Nubian Sandstone of Egypt. *Hippurites* (one of the Rudistes) occasionally penetrated into Northern Europe, but is only found as a rarity. The Hippurite Limestones are found to the south-east of the Alps, but to the north there is a huge development of coarse sandstone—the

Flysch or Vienna Sandstone—with few fossils. It must be remembered that nothing at all comparable with the Alps existed at this time—the formation of the Alps only dates from Mid-Tertiary.

7. In Neocomian times an arm of the Southern Sea pushed northwards from the Southern Ocean to the east of the Central Massif. Its connexion with the Wealden Lake is not known. Its onward progress was interrupted by a regression, during which the mottled clays of the Barremian were laid down.

8. The transgression continued later, and the sea invaded the Wealden Lake in Aptian times.

9. Then followed the great Cenomanian Transgression—the presence of sandy deposits over wide areas in the south-west should be noted.

10. The greatest extent of the Chalk Sea in France was in late Turonian or early Senonian times. It then commenced to retreat northwards, leaving, in highest Senonian times, little lagoons, in which the so-called "Montian" deposits (Calcaire pisolitique) were probably laid down.

The **Succession in France** is practically obvious from this account.

The **Succession in Belgium** is interesting, especially in the **Mons District.** Here the Cretaceous deposits were laid down in a shallow west to east synclinal basin on the edge of the Palæozoic massif. There was a regional depression, so that shallow water sands pass upwards into white chalk, but at the same time the syncline was growing so that the higher beds rest with slight unconformity on, and also overlap, the lower beds. Here deposition was almost, but not quite, continuous from the Cretaceous to the Tertiary, and the whole succession is:—

TERTIARY	Montian.	
CRETACEOUS	Danian (*sensu stricto*)=Tuffeau de Ciply.	
	Maestrichtian=Tuffeau de St. Symphorien.	
	Upper Senonian	White Chalk, phosphatized in the upper part.
	Lower Senonian	Chalk, passing down into shallower water beds.
	Turonian Cenomanian	Shallow-water glauconitic sands, marls, cherts, etc.
	Albian	
	Wealden	
PALÆOZOIC	Carboniferous, etc.	

The **Succession in Germany** in many ways resembles that in England. Succeeding the estuarine Purbeck are Wealden deposits—Weald Clay (Wälderthon) above, and sands (Deister Sandstone) below. These pass eastwards into marine deposits. The succeeding strata are probably Aptian followed rapidly by the "Lower Gault" of the Germans (which is either absent in this country, or represented by the Folkestone Beds).

ECONOMIC GEOLOGY OF THE CRETACEOUS.

1. Lime and Cement. The Chalk is enormously important. It is burnt for lime locally all over the country. Of still greater

importance is the manufacture of Portland Cement, which is chiefly in the hands of large companies, and consequently localized in centres. Some of the more clayey Lower Chalk can be used alone, but usually in the manufacture of Portland Cement a certain proportion of chalk is mixed with a certain proportion of clay, and the great centres of manufacture are situated where the two can be readily obtained. Some examples may be mentioned—

a. North Kent from Dartford to Gravesend and Grays in Essex. Chalk of *Micraster cor-anguinum* zone is mixed with mud dredged from the Thames. This assists in keeping the river clear for navigation.

b. Rochester and Chatham District—Chalk and mud from River Medway.

c. Greenhithe (N. Kent) Chalk and London Clay from neighbouring outlier. Also Denham (Middlesex).

d. Aylesford (North of Maidstone). Chalk and Gault Clay.

Many other examples might be given. Portland Cement has the valuable property of hardening under water.

2. Building Stones. The better varieties of "Kentish Rag" (Lower Greensand), especially from near Maidstone, are extensively used. The "Upper Greensand" of Surrey was formerly much quarried for hearthstone, *i.e.*, blocks sold for cleaning hearthstones, doorsteps, etc. Harder varieties of chalk are used occasionally for building, and especially for foundation work. Flints were formerly used almost exclusively in Upper Chalk country; they were usually trimmed on one face. Bricks are now, however, more generally in use, chiefly owing to the great quantity of cement or mortar which is used in flint building.

3. Road Metal. Kentish rag is extensively used, and is a first-class roadstone. Various Lower Greensand cherts are used locally and hard chalk as a foundation and on farm roads. Flint was formerly almost universally used for by-roads in Chalk districts

4. Brick and Tile Clays. The Gault is important, and articles, such as flower pots and tiles, of a fine red colour can be produced.

5. Fuller's Earth. Important deposits occur in the Lower Greensand of Nutfield, Surrey, and in the Midlands.

6. Sands. The Lower Greensand Formation yields some of the most important high-silica sands for the manufacture of glass in this country. The sand is quarried all along the outcrop, notable localities being Aylesford (Kent), Godstone and Reigate (Surrey), Aylesbury (Bucks), Leighton Buzzard (Beds) and Lynn (Norfolk). As a source of naturally bonded moulding sand the Cretaceous System is unimportant.

7. Refractory Substances, etc. Flint is much used in the Midlands for glazing, and was formerly exported, even as far as China.

8. Phosphatic Deposits. The beds of Phosphatic Nodules—such as the Cambridge Greensand and those found at various horizons in the Gault—were formerly much used. Phosphatized

Chalk occurs at Taplow and Winterbourne, but is not of great importance.

9. Iron-Ores. Not very important. The Claxby Ironstone of Lincolnshire was formerly worked.

10. Water Supply.

a. Lower Greensand. Yields good supplies locally.

b. The Chalk. The Chalk is one of the most important water bearing formations in the British Isles. The means of supply fall into two classes—

a. Shallow wells.
b. Artesian wells.

With regard to shallow wells, they are very frequent in country districts. Many towns in North Kent derive their principal supply from comparatively shallow wells in the Chalk of the North Downs.

Concerning artesian wells one may say generally that the lower marly layers of the chalk are impervious and that the chalk is underlain by impervious clay—the Gault. Where the chalk is folded into a syncline—as it is under London—a natural artesian basin is the result. Numerous artesian borings tap this supply in London, but the yield is extraordinarily variable, depending very largely on the fissuring of the chalk. Fissured chalk may yield a splendid supply, whereas a few hundred yards away a well in unfissured chalk may yield practically none. Thus a well sunk by Messrs. Selfridge, west of Oxford Circus in 1907, gave 3,500 gallons per hour. Another sunk the same year to the same depth just to the east of Oxford Circus by Messrs. Waring and Gillow, gave practically no supply at all.

Water from the chalk is naturally hard owing to the presence of Calcium bicarbonate in solution, but the hardness is temporary, and can be removed by boiling and by simple chemical means.

11. Agriculture and Scenery.

a. Lower Greensand. At times gives rise to barren sandy heaths; the more calcareous parts (Hythe Beds) are well wooded and more fertile. The higher beds are usually harder than the clays above and below, and give rise to an escarpment (as all round the Weald).

b. Gault. Low cultivated or marshy pasture land.

c. Chalk. Typical scenery is that of "rolling downs," the character of which depends on the presence or absence of shallow superficial deposits—especially clay-with-flints. Where the latter are absent the soil is extremely thin, and downs covered with short springy turf and providing pasturage only for a few sheep are the result. Areas of woodland—often largely cleared for cultivation—mark the patches of clay-with-flints. The chalk gives rise to magnificent escarpments and bold cliffs.

LIFE OF THE PERIOD.

The most important features of the Cretaceous fauna are the appearance of certain new echinoids and the abundance, in the Mediterranean region, of a group of peculiarly shaped Lamellibranchs, the Rudistes. Ammonites and Belemnites become

gradually less abundant, show degenerate characters (more or less uncoiled ammonites, other with sutures of Triassic types), and finally die out. In the Upper Cretaceous fishes and land-plants of modern types appear.

a. Plants. In the Lower Cretaceous Cycads and Conifers closely allied to later Jurassic types are found, in the Upper Cretaceous there is a sudden appearance of Angiosperms—especially Dicotyledons—more closely allied to the succeeding Tertiary floras and to modern plants. *Acer* (Maple), *Cinnamonum, Ilex* (Holly), *Quercus* (Oak) and *Populus* (Poplar) occur. The open-sea chalk of England does not, of course, furnish these fossils.

b. Vertebrata. Amongst fishes the Lower Cretaceous genera resemble those from the Jurassic, but types with imbricate scales closely resembling modern genera occur in the Chalk. Numerous reptiles are found, including many of the Jurassic genera, with the addition of certain new ones. Birds are rare and mammals extremely rare.

c. Arthropoda. Ostracods are often very common, as in the Chalk.

d. Mollusca. Among Lamellibranchs some of the abundant Jurassic genera die out. In particular *Trigonia* is almost extinct. In Upper Cretaceous the most abundant and universal genus is perhaps *Inoceramus*, which reaches a great size in the Chalk. In the southern seas the *Rudistes* of the Lower Cretaceous are followed by the bizarre *Hippurites* in the Upper—inequivalve lamellibranchs looking more like gastropods. Amongst Gastropods *Pleurotomaria* and other Jurassic forms remain abundant, and Tertiary genera, such as *Turritella*, *Cerithium* and *Aporrhais* appear. The Ammonites show signs of decadence in most of the groups. Side by side with normal forms are uncoiled ones, such as *Hamites*, *Turrilites*, *Baculites* and *Scaphites*. Essentially Cretaceous Ammonites are *Hoplites* (Gault), *Schlœnbachia* (Gault and Lower Chalk), *Acanthoceras* (Lower Chalk). The Belemnites die out with the Cretaceous, and the Nautiloids are represented almost solely by *Nautilus*.

e. Brachiopoda. Practically all the Cretaceous species belong to the broad "genera," *Terebratula*, *Terebratella*, *Terebratulina* and *Rhynchonella*.

f. Polyzoa. Encrusting forms are very common in the Chalk.

g. Echinodermata. Crinoids become scarce, and there are some curious free-swimming forms (*Marsupites* and *Uintacrinus*) in the Upper Chalk. Echinoderms, mostly irregular, are very important. The Cidaroids (*Cidaris*) and Diademoids (*Salenia*, *Peltastes*, *Phymosoma*) carry on Jurassic traditions, but the irregular Spatangoids are essentially Cretaceous. Many of them are heart-shaped (*Holaster*, *Hemiaster*, *Micraster*), and they are important zonal fossils.

h. Cœlenterata. Corals are not important.

i. Porifera. Sponges are common, especially in the Chalk (*Ventriculites*, *Doryderma*, etc.).

j. Protozoa. Small Foraminifera are abundant in the Chalk especially, and it is often difficult to distinguish some of the Cretaceous from recent species.

CHAPTER XVI.

THE OLDER TERTIARY PERIOD.

The Tertiary Era has often been described as the Age of Mammals. Not only are the strange Mesozoic reptiles replaced by animals whose direct descendants people the world at the present time, but the whole fauna and flora begins to assume a modern aspect. Familiar types of Lamellibranchs replace the Ammonites, and Dicotyledons reign in the Plant World.

The Tertiary has been divided into four Systems, the definition of which was originally based on the percentage of living species present amongst the fossils of each period. The percentages—which varied from less than 3½ in the oldest and up to 95 in the newest—no longer hold good, but the four systems are almost universally recognized. However, the Tertiary Systems are not of the same order of importance as the older Systems, in point of time the whole of the Tertiary Era is perhaps equivalent to one of the Palæozoic Systems. It is largely for that reason that some writers divide the Tertiary into two periods—the Palæogene and the Neogene. Very roughly these periods represent respectively the time before and after the great Tertiary Earth-Movements.

The classification of the Tertiary is then—

Neogene	Pliocene (= "more recent").
	Miocene (= "less recent").
Palæogene	Oligocene (= "few recent").
	Eocene (= "dawn [of] recent").

PALÆOGENE PERIOD—EOCENE.

It has been noticed that at the end of the Cretaceous Period the sea retreated from the English region, and the area was subjected to slight earth-movements and to very extensive denudation. When the sea returned in early Tertiary times it did so quite gently and gradually, and did not become very deep.

The Eocene deposits of the British Isles are almost entirely restricted to the South-East of England, where they are now found in the so-called " basins " (tectonic basins—see page 18) of London and Hampshire. The only other strata which may be of Eocene or Oligocene age are *a.* in the little basin of Bovey Tracey (Devonshire), and *b.* some of the inter-basaltic lacustrine deposits of the West Coast of Scotland. The latter are leaf-bearing marls, etc., which rest in erosion hollows on the surface of one lava flow, and are covered by another lava flow.

GEOGRAPHY OF THE EOCENE.

1. A partly enclosed sea, known as the Anglo-Franco-Belgian Basin, covered the South-East of England, the North-East of France and the greater part of Belgium (*Fig.* 63).

2. Into this sea there emptied at least two great rivers, bringing masses of sediment. One which has been called the Eocene Amazon flowed from the west or west-south-west and discharged into the sea in the Hampshire and London regions. The other, flowing probably from the south or south-east, poured into the basin in the Paris region.

3. It must be remembered that the earth-movements which culminated in the great " Alpine Storm " of Miocene times had commenced as early as the end of the Cretaceous. These early Alpine movements are an extremely important factor in the geography of Eocene times. They were doubtless responsible for the cyclic movements of depression which characterize the Eocene and Oligocene. The first period of depression resulted in the spread of the sea of the Landenian cycle. Then this sea gradually silted up. A new cycle commenced with renewed depression of the land surface and a renewed spread of the sea. The deltaic deposits round the river-mouths were covered by marine waters. Then, as the movement ceased, the rivers continuing to pour in fresh water, masses of sediment again extended estuarine conditions and restricted purely marine waters to the centre of the basin.

4. The history of the Eocene may be summarized as a repetition of such movements. The intermittent but

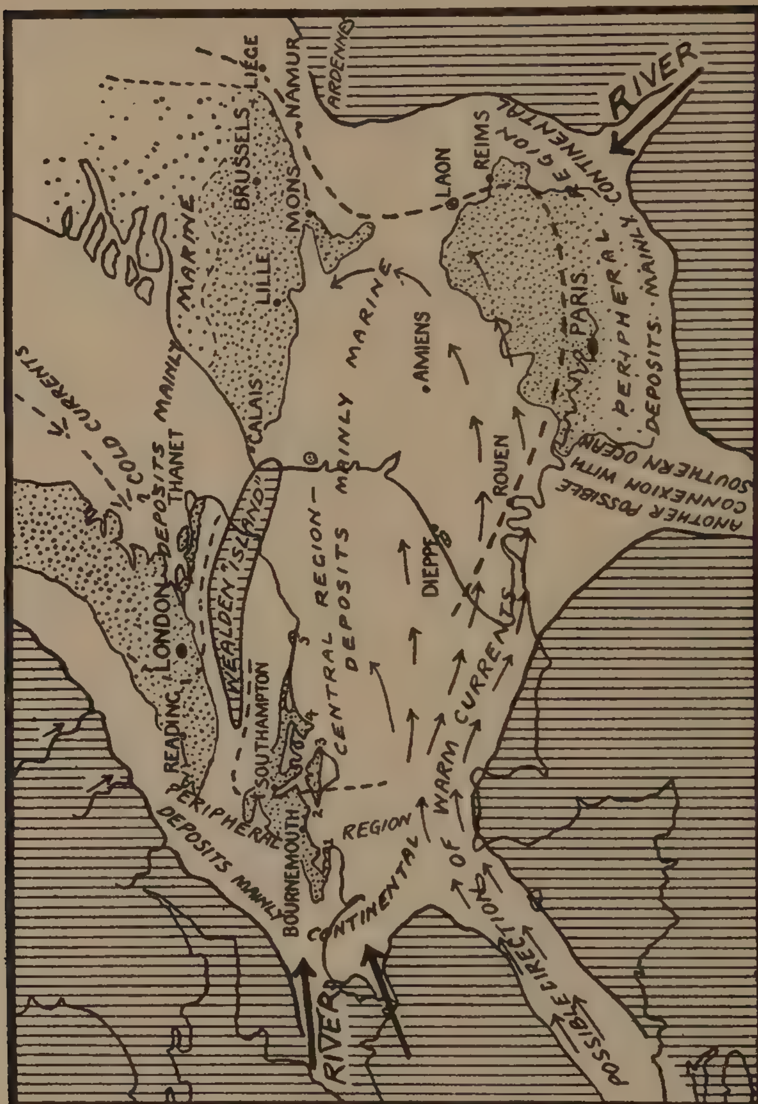

FIG. 63. Sketch map of the Anglo-Franco-Belgian Basin (Eocene). Existing areas of Eocene Strata dotted (where hidden under later deposits the dots are fewer). These areas are very approximate. Key to Coast sections in the Hampshire Basin (see *Fig.* 64). 1 = Studland Bay; 2 = Alum Bay; 3 = Whitecliff Bay; 4 = Selsey Bill; 5 = Newhaven. (*L.D.S.*)

gradual uplift of the Wealden anticline seems responsible for many of the phenomena associated with the inception of each cycle, though intermittent regional subsidence is obviously important as shown by the diagram on p. 288. The principal axis of this fold runs approximately east and west, trending somewhat southwards towards the east. The Wealden Dome, as it is more correctly termed since it pitches at both ends, must have formed a large submerged shoal or even an island in the Anglo-Franco-Belgian Basin.

5. We have already seen that in Triassic, Jurassic and Cretaceous times a great Southern Ocean existed in the region of the present Mediterranean. The same ocean, stretching from Spain to the eastern end of the Himalayas, persisted in early Tertiary times. It covered the whole of the Mediterranean Sea and the lands on either side, including the regions now covered by the great fold ranges of the Alps, Apennines, Carpathians, Balkan Mountains, Caucasus, and stretching to the eastern end of the Himalayas. An extensive fauna flourished in this ocean, some of the most remarkable members are the numerous species of Nummulites. So abundant are they that the bulk of the deposits of the Southern Ocean (generally known as the Tethys) are often built up of their remains.[1] The Tertiary has even been called the Nummulitic Period.

6. It would appear that the Anglo-Franco-Belgian Basin was connected with the Southern Ocean for certain short periods during Eocene times.[2] The connexion seems to have been effected during some of the more markedly marine periods, and to have been either—

a. between the massifs of Brittany and Central France, or

b. north of the massif of Brittany, *i.e.,* along the southern part of the present English Channel—

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[1] Along the northern border of this ocean an enormous series of soft sandstones, shales and conglomerates—collectively known as the Flysch or Molassen—was accumulated. It ranges in age from Cretaceous to Miocene, but the bulk is Palæogene.

[2] The connexion was by no means direct, but via the Basins of South-Western France (Aquitaine). The writer is indebted to MM. H. Douvillé and M. Cossmann for several suggestions embodied here.

the more probable as fragments of marine Eocene beds have been dredged up from the English Channel.

The marine faunas of the Eocene Beds of the Anglo-Franco-Belgian Basin may be regarded as consisting very largely of species brought in by warm currents—more or less comparable with the Gulf Stream—from the Southern Ocean at such times when connexion was established. Similar currents probably brought the Rudistes into the Chalk Sea. Thus it is found on the whole that the marine faunas in the Basin become impoverished as one passes northwards from the Paris region into England. Moreover, four out of the five marine periods are characterized by isolated species of *Nummulites*. The species of *Nummulites* which occur are not connected with one another phylogenetically, and so cannot have evolved from one another *in situ*. On the other hand, they are found to be individual members of continuous evolutionary series found in the Southern Ocean. In other words, the Nummulites were evolved in the Tethys—the Southern Ocean—and at certain periods only, when connexion was temporarily established with the Anglo-Franco-Belgian Basin, did certain species overflow into that region.

7. Little can be said regarding the north-eastern extension of the Anglo-Franco-Belgian Basin. It was probably closed towards the north, but the agency of cold currents coming from that direction has been held to account for the distribution of certain members of the Eocene faunas, such as the lamellibranch *Cyprina*.

8. Besides the two main sources of sediment which were the two great river systems already mentioned as draining into the basin, there were probably other small sources, especially at certain periods. Among these may be mentioned, in Upper Landenian times, streams from the north-west along the northern border of the London "Basin" and streams from the south-east in Belgium. The Belgian shore of the Basin on the whole, however, seems to have been flat and tranquil since the main deposits (clays, etc.), pass gradually into coarser sediment (glauconitic sands), but do not exhibit any very coarse coastal deposits or masses of sand of terrestrial origin. Such is the case with the London Clay. The sea in the

Belgian area remained shallow during the whole of the Eocene Period, and several rocky islets or submerged shoals, such as those formed by the hard intrusive mass of porphyrite at Quenast interrupted the smoothness of the sea-bottom. The Quenast rock, for example, is covered directly by London Clay, and towards the Ardennes Lutetian rocks overlap on to Palæozoic strata.

9. The oscillation of the water-level in the Anglo-Franco-Belgian Basin enables the beds to be grouped into a series of "Cycles of Sedimentation," each cycle commencing with the deposits of a marine invasion, followed by shallow then deep water marine beds. These in turn gradually become of shallower-water type as estuarine conditions spread seawards, and so pass up into continental deposits (see page 14). The latter are cut off abruptly by the marine invasion, which commences the next cycle.

10. The deposits of the Anglo-Franco-Belgian Basin form essentially one whole, and each horizon should be considered over the whole region. Owing, however, to later earth-movements and denudation the deposits are now actually found in four principal regions — the so-called "Basins" of London, Hampshire, Paris and Belgium. It seems better to apply the term "basin" to an original area of deposition rather than to the extensive though virtual outliers now left as a result of folding and denudation.

CLASSIFICATION OF THE EOCENE BEDS.[1]

In each of the four areas five Cycles of Sedimentation may be distinguished. In the Belgian region a lower cycle—the Montian—which is possibly represented by the Calcaire pisolitique in the Paris Region, but which is absent in England, has been separated. The Cycles common to all areas are—

5. Bartonian (Barton in Hampshire).
4. Ledian (Lede in Belgium).
3. Lutetian (Lutetia = Paris).

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[1] L. D. Stamp, "On Cycles of Sedimentation in the Eocene Strata of the Anglo-Franco-Belgian Basin." *Geol. Mag.*, vol. lviii., March-May, 1921.

2. Ypresian (Ypres in Belgium).
1. Landenian (Landen in Belgium).

THE EOCENE IN ENGLAND.

The two main existing areas of British Eocene Rocks may be considered separately.

A. Hampshire.[1] Eocene strata cover a roughly triangular area, with a base extending from the Dorset-Devon Boundary eastwards to Worthing, and by outliers to Newhaven, and an apex in the neighbourhood of Salisbury. The region is limited on the south by the post-Oligocene monoclinal fold which passes through the Isle of Purbeck and the Isle of Wight. The beds are predominantly continental in character in the west, but become mainly marine in the east. Thus wedges of continental strata (thicker in the west) alternate with wedges of marine strata (thicker in the east, that is, towards the centre of the Anglo-Franco-Belgian Basin). This is splendidly shown in a series of coast exposures—virtually sections across the monoclinal fold already referred to above. These sections are—

a. Studland and Bournemouth Bays.
b. Alum Bay, at the western end of the Isle of Wight.
c. Whitecliff Bay, at the eastern end of the same island.
d. Coast of Selsey Bill, and, further east, the cliffs of Newhaven.

The relation between the beds may best be shown by means of a diagrammatic section from west to east (*Fig.* 64, reproduced, by permission, from the Geological Magazine, 1921).

1. Landenian. Detailed mapping of the zones of the Chalk—notably in the Isle of Wight — shows that the lowest Eocene deposits rest on a highly eroded surface of the Chalk.

a. Marine Landenian. The lowest layer, known in the London district as the Bullhead Bed, consists of green-coated, largely unworn flints, with a few small rolled pebbles, set in a matrix of coarse glauconitic sand, often very clayey and ferruginous. The interpretation given to this bed is that the unworn flints and the clayey matter represent the result of Pre-Eocene solution and weathering of the Chalk (*i.e.*, pre-Eocene clay-with-flints) that

[1] Useful summaries are given in the "Geology of the Country around Lymington and Portsmouth" (1915) and a "Guide to the Geology of the Isle of Wight" (1922), *Mem. Geol. Surv.* See also British Regional Geology : The Hampshire Basin, 2nd Ed., 1948.

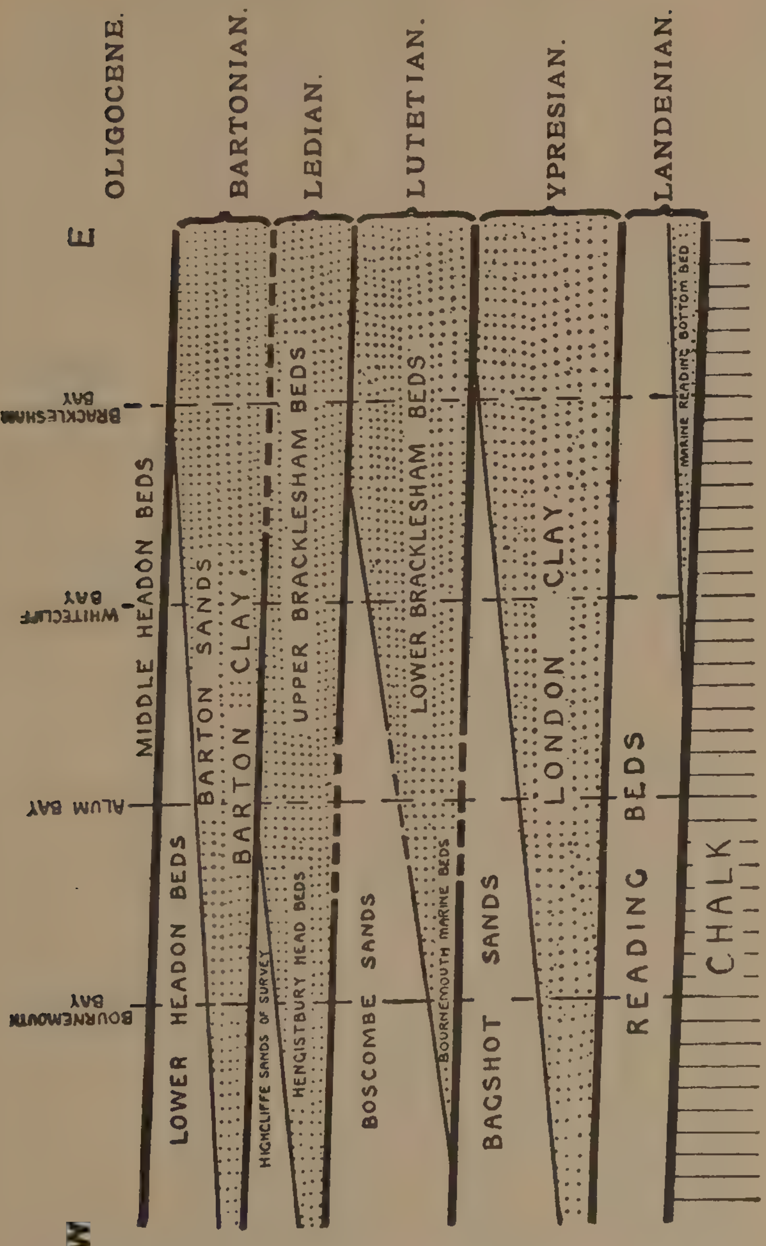

FIG. 64. Cycles of Sedimentation in the Eocene Strata of the Hampshire Syncline. (*L.D.S.* reproduced from the *Geological Magazine,* April, 1921, by permission of the Editor.)

the rolled pebbles, slight rounding and green-coating of the larger flints are the work of the invading Eocene sea. The green coating seems to consist of a mineral allied to glauconite, which can only be formed in sea-water. The marine invasion is shown to be a very gentle one by the almost unworn character of the flints. Practically no fossils occur in this bed, though a few fragments of Oysters have been recorded to the west.

The basal layer is followed by a bed of marine glauconitic sand, some 33 feet thick at Newhaven, but thinning rapidly westward. The sand is unfossiliferous, but corresponding beds across the Channel yield fossils which show that this sand must be of the same age as the Bottom Bed of the Woolwich Series of the London District (Lower or Marine Landenian).

b. Upper or Continental Landenian strata succeed conformably, and are known as the Woolwich and Reading Beds. In the west are the fluviatile and lacustrine Reading type, consisting of gravels, coarse current-bedded sands *without* glauconite, and mottled clay. Only in the extreme east at Worthing and Newhaven is the estuarine Woolwich type found, consisting of well-bedded dark clays crowded with fossils. Except for traces of plants, fossils are practically absent in the Reading type, those found in the beds of Woolwich type are few in point of species, but abundant in point of actual numbers of individuals. This is particularly characteristic of estuarine deposits. They include *Ostrea bellovacensis* (often in thick beds), *Cyrena cuneiformis*, *Melania inquinata* and *Potamides funatus*.

2. Ypresian. The Upper Landenian, the most widespread of the continental episodes, is succeeded by the Ypresian, the most widespread of the marine episodes of the Eocene.

a. Marine Ypresian is represented by the London Clay. The "Basement Bed" consists of a bed of well-rolled black flint pebbles, and a few feet of fine-grained sands. The marine clay, as one would expect, decreases in thickness from east to west, and at the same time becomes more sandy. About 340 feet in Portsmouth Harbour, 320 feet in Whitecliff Bay and 233 in Alum Bay, it is only about 80 or 100 feet in Studland Bay, and decreases still more further west. It passes up quite gradually into the continental Ypresian (Lower Bagshot Sands). The clay is unfossiliferous in most localities, but a magnificent fossiliferous series was exposed many years ago in Portsmouth Harbour excavations. *Ditrupa plana* and *Cytherea* occur especially in the Basement Bed; *Pholadomya margaritacea*, *Modiola simplex* and *Panopæa intermedia* in the mass. To the east, at Bognor, there is a band of calcareous sandstone (Bognor Rock) full of fossils (*Axinæa brevirostris*, *Pinna*, *Vermicularia*). In most places the clay is fairly homogeneous, except for bands of septaria and beds of fine sand (the latter in the upper part), but when one goes northwards, *i.e.*, towards the area of the Wealden uplift, bands of rolled flint pebbles appear. These were probably derived from the Chalk of the Weald.

b. Continental Ypresian. A series of gravels, coarse sands, often false-bedded or lignitiferous, and pale grey pipeclays, col-

lectively known as the Lower Bagshot Beds. Probably at least 500 feet thick in the west (Bournemouth Bay), in the east there are only about ten feet left to the north of Selsey Bill, proving derivation from the west. Near Bournemouth a lower "Pipe-clay Series" has been sometimes separated from an upper "Bournemouth Freshwater Series." Interesting plant remains occur.

3. Lutetian (corresponds approximately to the Lower Bracklesham Beds).

a. Marine Lutetian. Well seen in Whitecliff Bay. At the base a pebble bed and coarse glauconitic sands occur, followed by clayey and glauconitic sands, with bands of fossils. The latter are also abundant, but rarely exposed, on the muddy shores of Selsey Bill. Fossils include *Nummulites lævigatus, Venericardia planicosta, Ostrea flabellula* (=*O. plicata*), *Sanguinolaria hollowaysi* and *Turritella imbricataria*. There is evidence that the sea was not so deep as in Ypresian times, and a seam of lignite occurs as far east as Whitecliff Bay. In Alum Bay the deposits are decalcified and difficult to separate. In Bournemouth Bay the "Bournemouth Marine Series" with crabs (*Callianassa*) are Marine Lutetian.

b. Continental Lutetian. Lignitic sands, with seams of lignite pass westwards into the Boscombe Sands—beds of coarse pebbles bleached by atmospheric weathering (?) and false-bedded sands with fruits (*Nipadites*).

4. Ledian (corresponds approximately to the Upper Bracklesham Beds).

a. Marine Ledian, succeed the Marine Lutetian beds immediately at Selsey Bill (*i.e.*, the interpolated Continental Lutetian dies out eastwards), but there is a marked faunal break. Glauconitic sands and clays characterized by *Nummulites variolarius*. Represented by the Hengistbury Head Beds in Bournemouth Bay. There is a band of foraminiferal limestone near the top of the Ledian at Selsey Bill.

b. Continental Ledian is feebly developed. Highcliffe Sands (as defined by the Survey) are pale sands with tiny seams of pipe-clay.

5. Bartonian (Barton Clay, Barton Sands and Lower Headon Beds).

a. Marine Bartonian. At or near the base is a band of coarse sand or pebbles, with a band crowded with *Nummulites wemmelensis* (=*N. prestwichianus*),[1] followed by the Barton Clay, which is very rich in fossils (*Voluta athleta, Cassidea ambigua, Fusus longævus, Crassatella sulcata*, etc.), which have a decidedly warm water aspect. The succeeding Barton Sands have a band swarming with *Chama squamosa* near the base, followed by brackish water fossils (*Cerithium*) in the upper part.

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[1] *N. wemmelensis* and *N. prestwichianus* may be two slightly different races of the same species. They are both degenerate forms and probably evolved *in situ*.

b. Continental Bartonian (=Lower Headon Beds) succeed quite gradually. Consist of marls and lignitic sands, with fresh-water fossils, with a freshwater limestone at the top (*Planorbis* and *Limnæa*). At Hordle, on the Hampshire Coast, these beds have yielded numerous reptilian and mammalian remains.

B. London District.[1]

In the London Syncline the succession of Eocene strata is far less complete, post-Ypresian beds only being preserved in the Bagshot area of Surrey. In general they resemble the deposits in the Hampshire District by being predominantly Continental in the west, and, as far as the sequence goes, they are entirely marine in the east. The relation of the beds to one another is again shown by means of a diagrammatic section from west to east (*Fig.* 65).

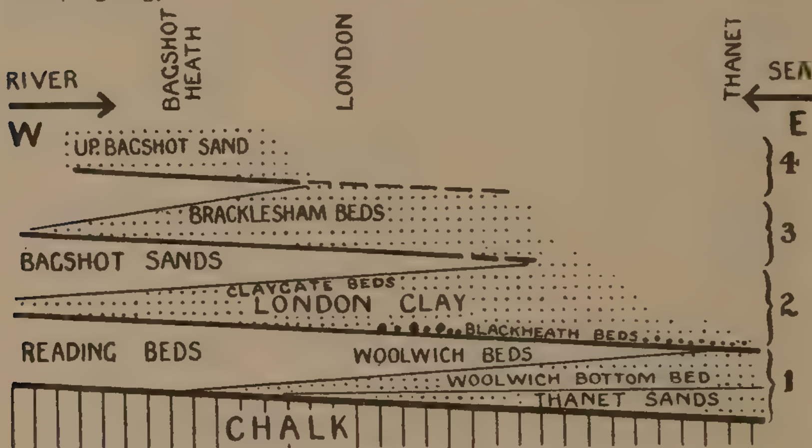

FIG. 65. Cycles of Sedimentation in the Eocene Strata of the London Syncline. 1, Landenian; 2, Ypresian; 3, Lutetian; 4, Ledian. The marine beds are dotted, no indication of lithology is implied. (*L.D.S.*)

1. LANDENIAN (Thanet Sands and Woolwich and Reading Beds).

a. Marine Landenian. At the base is the "Bullhead Bed," as in the Hampshire district. The overlying Thanet Sands are marine glauconitic sands, fine grained and clayey in the lower part, becoming coarser in the upper part. As one would expect, the oldest beds are in the east—bands of hard tuffeau with *Pholadomya cuneata* at Pegwell Bay, Ramsgate. The overlying sands are fossiliferous at Herne Bay (*Cyprina morrisi*), but rarely so near London, and they die out near Leatherhead. Succeeding the Thanet Sands, and separated from them by a band of well rolled

[1] Guide to the Geology of London, 2nd Ed., 1922, *Mem. Geol. Surv.*; British Regional Geology: London and Thames Valley, 2nd Ed., 1947.

flint pebbles are the glauconitic sands of the "Bottom-bed" of the Woolwich Series. These constitute a zone of *Cyprina scutellaria,* and yield also *Pectunculus terebratularis* and *Corbula regulbiensis.* The basal pebbly layer is absent in the extreme east. Doubtless this break in the midst of the marine Landenian is due to a movement of uplift of the Wealden dome. The pebbles die away to the north.

b. Continental Landenian succeeds gradually and conformably, and is only absent in the extreme east. As in the Hampshire District, there are two types—the Reading type in the west and north, the Woolwich type in the centre. To the west of London the Reading type, with its fluviatile gravels, false bedded sands and mottled clays, rests directly on Chalk, with a thin basal layer, which shows slight traces (in the presence of *Ostrea*) of marine conditions. To the north of London quite coarse river-gravels appear at the base, but the Chalk below them (as at Harefield) may be bored to the depth of a foot by the marine worm "*Terebella*" *harefieldensis*. The Woolwich type resembles the development at Newhaven, fossils are similar—with the addition of *Cyrena cordata*, and the estuarine muds become partly freshwater in the upper part, containing bands with freshwater fossils (*Paludina*). To the east the Woolwich type dies out about Sittingbourne, and the whole of the Landenian becomes marine.

2. YPRESIAN.

a. Marine Ypresian. The bulk of the marine Ypresian is made up of the London Clay, but the lowest beds of the cycle are of very great interest. They are the Oldhaven or Blackheath Beds.

Blackheath Beds. The Woolwich type of Upper Landenian consists of evenly-bedded clays deposited in estuarine flats. A slight earth-movement would cause the sea to invade the whole area. This is exactly what happened in early Ypresian times. It may have been that a general depression resulted in the invasion by the sea of the whole Woolwich estuarine area and that during the period of subsidence the coastal pebble beaches were redistributed by wave action and the pebbles more perfectly rounded. Possibly a slight movement of uplift of the Weald was accompanied by a depression of the basin to the north and caused great masses of pebbles to move downwards from the area of uplift into the sea so formed. In the east the beds are sandy (Oldhaven type), in the London District they are pebbly (Blackheath type). The pebbles are all perfectly rounded flint and typically black (*i.e.,* not bleached), showing that they were deposited as submarine shoals. The beds rest in eroded hollows in the underlying Landenian, and show every sign of strong current action—false-bedding on a large scale, great variation in character and thickness. The fauna of these beds is of great interest. In the east (Oldhaven Beds) it is entirely marine, but wherever the beds rest on Woolwich estuarine beds the fauna of the Blackheath Beds may be divided into—

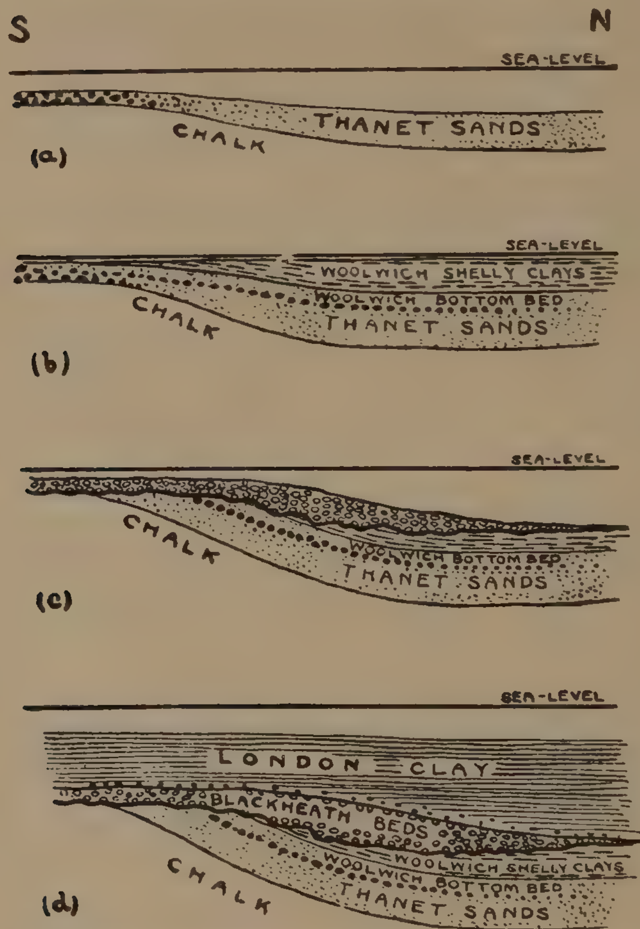

FIG. 66. Diagrams showing the manner in which the Lower Eocene Deposits of the London Syncline are banked against the Wealden uplift. Each of the four diagrams is an idealized section drawn from south (region of Wealden uplift) to north in the North-Western Kent area. (a) Conditions during deposition of the Thanet Sands. Note the southward passage of the Thanet Sands into shallower water or littoral deposits. Here one sees angular or partly rolled flints, resulting from the marine denudation of the slightly uplifted Chalk of the Wealden anticline. (b) Conditions during deposition of the Woolwich Estuarine Shell Beds. A slight movement of uplift in the south has caused a thin pebble bed to be formed between the Thanet Sands and the Woolwich Bottom Bed. This pebble bed decreases in thickness to the north. Then the shallow sea has become silted up owing to the deposition of the Woolwich Shell

i. Species which were living in the Woolwich estuaries at the time of their invasion by the sea, and which struggled to live on (*Cyrena cuneiformis, Potamides funatum*).
ii. Species which flourished under the changing conditions (*Cyrena tellinella*).
iii. Marine species which had been living in the Lower Landenian Sea, but which had migrated away with the oncoming of estuarine conditions, but which now return, somewhat changed (*Corbula regulbiensis*).
iv. Marine species, which appear for the first time, but which become characteristic of the overlying marine Ypresian. (*Nemocardium plumstedanum.*)

It should be noted that the Blackheath Pebble-Beds occur to some extent banked up against the Wealden Dome (see *Fig.* 66).

London Clay. The London Clay marks a return to tranquil marine conditions, and the sea continued to spread quietly in all directions. The base is marked by a Basement-Bed consisting of a band or bands of well rolled pebbles and sand or sandy clay, with shallow water marine fossils (*Cytherea*). The London Clay is a stiff blue clay with septaria, and increases in thickness from less than 15 feet in the extreme west to over 500 in the east. It is fossiliferous at various horizons (*Pholadomya margaritacea, Cyprina planata, Modiola elegans,* and towards the upper part *Pecten corneolus*, *Protocardia nitens* and numerous gastropods). As far east as the Isle of Sheppey are drifted fruits (*Nipadites*), cones and wood. Bones of turtles, etc., in the same locality may indicate proximity of land to the south (Wealden Dome). The clay becomes sandy in the upper part (Claygate Beds) and passes gradually into continental Ypresian.

b. Continental Ypresian (Lower Bagshot Sands). A series of unfossiliferous current-bedded sands with small lenticular seams of pipe-clay. To the east they pass into the Bagshot Beds of Essex, which Wooldridge has shown are fine grained *marine* sands identical with the highest Ypresian of Belgium.

3. LUTETIAN (Middle Bagshot or Bracklesham Beds).

a. Marine Lutetian. Represented by glauconitic sands and sandy clays, in which fossils are locally common. They include typical Lutetian species, *Corbula gallica, Venericardia planicosta, Turritella imbricataria,* many fish teeth, and, most important of all, *Nummulites lævigatus.*

FIG. 66 (*continued*).

Beds, and its place taken by an estuarine lagoon. (c) Conditions during the deposition of the Blackheath Beds. Pronounced uplift in the south has caused the movement of a great mass of pebbles towards the newly depressed region of the north. Note the unconformable relationship of these pebble beds with the underlying strata and their decrease in importance towards the north. (d) Conditions during the deposition of the London Clay. Continued depression has allowed the deposition of a thick mass of marine clay in comparatively tranquil deep-water conditions. (*L.D.S.* reproduced by permission of the Council of the Geologists' Association.)

b. Continental Lutetian. The above mentioned sands become lignitiferous and more clayey in the upper part.

4. LEDIAN (Upper Bagshot Sands, misnamed Barton Sands).

a. Marine Ledian. A series of yellow and white sands, with a pebble bed at the base. They are the youngest Eocene Beds of the London District. A small series of fossils has been recorded, including *Nummulites variolarius*, which, if correct, shows that the beds are Ledian and not Bartonian.

It has been noticed that the floras of the Eocene period show consistently warm or sub-tropical characters. The marine faunas, however, seem to vary. Thus the Lutetian fauna has a more tropical character than either the Ypresian or the Bartonian, whilst that of the Landenian has a decidedly more northerly appearance. These features are doubtless due to the variation in the strength of the currents from the warm Southern Sea, mentioned on page 280. It will be of advantage to compare the development in the other parts of the Anglo-Franco-Belgian Basin —in the Paris and Belgian areas.

C. Paris District.

1. LANDENIAN. The marine Landenian has been divided into three zones, each one distributed over a wider area than the preceding, thus demonstrating the gradual transgression of the sea. The overlying Continental Landenian is exactly comparable with the English representative—it falls into the same two types (Woolwich and Reading), and has the same fossils.

2. YPRESIAN. The Sinceny Beds were formed under precisely the same conditions as the Blackheath Beds and their fauna can be divided into the same four groups. The place of the London Clay is taken by the Cuise Sands, characterized by *Nummulites planulatus* (*N. elegans*). The nummulite was evidently unable to live in the muddy waters of the London Clay Sea, but in Northern France (near Calais) the two types of deposit have been found interbedded—layers of sand with *Nummulites planulatus*, alternating with layers of clay with *Pholadomya margaritacea.* The continental Ypresian is less developed than in England.

3. LUTETIAN. The marine Lutetian has been divided into four zones, which again show the gradual transgression of the sea. The most important bed is the famous "Calcaire grossier," a fine soft foraminiferal limestone much in demand as a building stone. Certain beds of the Lutetian simply consist of a mass of *Nummulites lævigatus.* The continental Lutetian consists of brackish water marls and mottled clays.

4. LEDIAN. The marine beds of this age are of shallower water type.

5. BARTONIAN. The marine representative is quickly succeeded by a thick mass of gypsum and gypseous marls, which indicate that this portion of the Anglo-Franco-Belgian Basin was probably cut off and dried up. Towards the higher part there is a very brief marine incursion (Ludian marls).

D. Belgium.

Belgium differs from other parts of the Basin in that the marine episodes succeed one another without the interpolation of definite continental periods (except Landenian). This is due to the absence of a great river bringing sediment into this area. The marine deposits of each cycle are, however, separated from one another by small ravinements or slight unconformities. For details reference should be made to papers already quoted.[1]

Recapitulating, the five cycles and their characteristic marine fossils are—

6.	Bartonian	*Nummulites wemmelensis.*
5.	Ledian	*Nummulites variolarius.*
4.	Lutetian	*Nummulites lævigatus.*
3.	Ypresian	*Nummulites planulatus.* *Pholadomya margaritacea.*
2.	Landenian	*Cyprina (Arctica) scutellaria.* *Cyprina (Arctica) morrisi.*
1.	[Montian in Belgium only.]	

PALÆOGENE PERIOD—OLIGOCENE.

Undoubted Oligocene deposits only occur in England in the Isle of Wight and the adjacent mainland. They surmount the Eocene Beds of the Hampshire District already described, and occupy the centre of the main syncline (see page 300).

GEOGRAPHY OF THE OLIGOCENE.

1. We have already seen that the Anglo-Franco-Belgian Basin gave evidence of having been cut off in late Eocene times and of drying up—especially in the Paris region. The highest marine faunas of the Bartonian (Marls of Ludes in France and Barton Sands in England) appear to have evolved *in situ* in the Basin itself and not to have come in from outside regions.

2. The commencement of the Oligocene is marked by a new marine invasion, bringing with it numerous quite new and typically Oligocene molluscs. Although the sea probably flowed over the greater part of the largely silted up Anglo-Franco-Belgium Basin, conditions did not become purely marine for a long time — the old Eocene brackish water species in many cases lived on. Accord-

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[1] L. D. Stamp, *Geol. Mag.*, 1921; "The Geology of Belgium," *Proc. Geol. Assoc.*, vol xxxiii. (1922).

ingly both in the English and French regions we find the initial marine invasion followed by a considerable period in which brackish and eventually freshwater conditions prevailed—completing one Cycle of Sedimentation. A new marine invasion marks the commencement of another Cycle—the latest of which traces remain in England. The same great river was flowing into the Hampshire region as in Eocene times.

3. One important question is the route by which the Oligocene faunas came. The probable answer is from the Southern Ocean via Germany and Belgium. In other words, the Oligocene fauna came from the east, whereas the Eocene faunas came via the south-west.

THE OLIGOCENE IN ENGLAND.

The Oligocene Beds of England (Isle of Wight and Hampshire mainland) have been divided in England into small divisions, which have a purely local significance. With reference to foreign deposits they comprise representatives of one Cycle of Sedimentation and part of a second.[1]

STAMPIAN—*a.* marine = Hamstead Beds (marine).

SANNOISIAN	*b.* continental	Hamstead Beds (lower part)	freshwater and brackish.
		Bembridge Beds	
		Osborne Beds	
		Upper Headon Beds	
	a. marine	Middle Headon Beds and Brockenhurst Beds.	

1. SANNOISIAN (from Sannois, near Paris).

a. Marine. Like all the marine beds of the underlying Eocene, the marine Sannoisian are thicker in the east than they are in the west. They are 120 feet thick in Whitecliff Bay, and are well developed at Brockenhurst in the New Forest, but have thinned to 33 feet in Alum Bay, where the upper part of the Middle Headon Beds is already continental (estuarine and freshwater). At Brockenhurst three marine zones have been distinguished :—

iii. Zone of *Meretrix* [*Venus*] *incrassata.*
ii. Zone of *Voluta geminata.*
i. Zone of *Voluta suturalis.*

The higher zones seem to overlap the lower to the west, and probably only the highest is represented in Alum Bay. The marine Sannoisian consist of sandy glauconitic clays.

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[1] This is here published for the first time.—L.D.S.

b. Continental. A succession of sands, marls and limestones with freshwater and terrestrial fossils, with some bands more estuarine in character and even (in the east at Whitecliff Bay) with a few marine fossils.

i. Upper Headon Beds—sands, clays and limestones, with freshwater fossils (*Limnæa longiscata* and *Planorbis euomphalus*).

ii. Osborne Beds. Pale marls, with concretionary limestones (*Limnæa*, *Planorbis discus*, *Viviparus lentus*) in the west; passing eastwards into marls and sands, with similar fossils, together with *Melania acuta* (indicates slightly brackish water) and into greenish clays and sands (Whitecliff Bay). Mammalian and Reptilian remains have been found in quantity.

iii. Bembridge Beds—lower part consists of a thick and constant limestone with terrestrial and freshwater molluscs and mammalian remains (all of which occur in the Paris Sannoisian). The upper part consists of marls with plant remains, and, in the east at Whitecliff Bay, some marine fossils. Leaves and insects occur in the highest part at Cowes.

iv. Hamstead Beds—lower freshwater and estuarine beds—consist of black and green clays, with bands of freshwater fossils (*Viviparus lentus*), some of brackish (*Cerithium plicatum*), and some with plant remains.

2. STAMPIAN (from Etampes in France).

a. Marine. Only about 20 feet of blue marine clays are left at Hamstead, in the Isle of Wight, to represent the Stampian. The fossils include *Corbula* sp., *Ostrea callifera* and *Athleta rathieri*.

An outlier of freshwater limestone (probably Bembridge Limestone) occurs at Creechbarrow Hill in Dorsetshire.

The Bovey Tracey Basin of Devonshire.

An interesting series of freshwater clays, sands and lignites occupies a small basin, about nine miles long, and surrounded by hills of Carboniferous and Devonian rocks. The deposits reach nearly 600 feet in thickness. The exact age depends on the evidence afforded by the plant remains, and the most recent account indicates a late Oligocene age. The plants are those of the granite ravines which surround the basin—warm temperate forms—together with northern forms, which may have lived on the higher ground of Dartmoor, and a few aquatic species. Leaves include those of *Magnolia*, various species of *Nyssa*, *Sequoia*, etc.

The Mull Leaf Beds of Scotland.

Many plant remains have been obtained from bands of sand and shale intercalated in the Tertiary lava flows. The plants have been claimed to indicate a Miocene age, and also a very early Eocene age. They include *Ginkgo, Taxus, Sequoia, Populus*, etc.

THE OLIGOCENE IN FRANCE.

The succession in the Paris region has been classified as follows :—

Chattian.
Stampian, including the Fontainebleau Sands.
Sannoisian, including the Marls above the Gypsum.

Like our English Sannoisian, the French deposits of the same age consist of marls, with many estuarine species and a few marine Oligocene species, but in which the mammalian and reptilian remains are definitely Oligocene.

The Stampian marks a much more definite and more extensive marine invasion. The Jeurre Sands, at or near the base, have a littoral fauna, the succeeding horizons of the Fontainebleau Sands (Morigny, Pierrefitte, etc.) have an abundant marine fauna (*Pectunculus obovatus*).

The Chattian is less clearly differentiated, and includes freshwater limestone.

THE OLIGOCENE IN BELGIUM.

Chattian.
Rupelian = Stampian.
Tongrian = Sannoisian.

The lower Sannoisian beds are clays with *Meretrix incrassata* and other fossils common to the Middle Headon and Brockenhurst Beds of England. The Stampian Beds have sands with *Pectunculus obovatus* (compare Paris district).

THE OLIGOCENE IN GERMANY.

A great Oligocene sea covered most of Germany, and the deposits are divisible into three, as in Belgium. The lower Oligocene yields the famous amber of the Baltic Coast, the Middle is the " Rupel-thon " or Septarian Clay.

LIFE OF THE PERIOD (PALÆOGENE).

In contrast with the Cretaceous fauna and flora, in the Tertiary one notes the absence of the great marine Saurians, and, save rarely, of bony fish (Ganoids); the absence of Ammonites and Belemnites, and the disappearance among the Lamellibranchs of the Rudistes (*Hippurites* and *Radiolites*), *Inoceramus* and *Trigonia* (except in a few rare cases). There is also a great reduction in Brachiopods, but a great development of sinupalliate Lamellibranchs. Amongst vertebrates the development of snakes, normal birds and placental mammals is to to be noted; among plants of Angiosperms.

The life of the Palæogene period is distinguished from that of the Neogene chiefly by its vertebrates and by the greater development of large Foraminifera. In general the Palæogene flora, and to a less extent the fauna, has a more tropical aspect than in the Neogene Period.

a. Plants. The Dicotyledons include—

(i.) tropical forms: *Cinnamonum.*
(ii.) sub-tropical forms: *Ficus* (Fig), *Laurus* (Laurel), *Magnolia.*
(iii.) temperate forms: *Acer* (maple), *Quercus* (oak), *Salix* (willow).

Monocotyledons include various palms.
Conifers include *Sequoia.*

b. Vertebrata. The early Eocene mammals are mostly small and primitive, with 44 low-crowned teeth and five-toed limbs. Ungulates (hoof-bearing mammals) become important, and, in common with other mammals, are larger and more specialized in Middle Eocene and later times. *Palæotherium* (ancestor of tapirs and rhinoceros) and *Anoplotherium* (ancestor of horses, etc.) are particularly interesting Oligocene forms. The ancestors of the elephants have now been found in the Palæogene of Africa. Carnivora and Lemurs appear, but not true apes. Amongst fish one may note the great abundance of sharks (*Lamna, Otodus*). The Ganoids survive into the Eocene, and then become extinct.

c. Arthropoda. Differ little from those living at the present day. Crabs are important.

d. Mollusca. Both Lamellibranchs and Gastropods are very abundant. The Lamellibranchs are mostly sinupalliate, that is, the pallial line or line of attachment of the mantle to the interior of the shell has an indentation or sinus. The Gastropods are still more abundant, they are mostly siphonostomatous, that is, the opening of mouth of the shell is not circular or entire, but the lip is drawn out into canals. Cephalopods are unimportant, *Nautilus* (still living) being almost the only one worthy of mention.

e. Brachiopoda. Rare.

f. Echinodermata. Both Regular and Irregular Echinoids are very abundant, especially in the warm clear waters of the Mediterranean Sea (Tethys).

g. Protozoa. Nummulites is an essentially characteristic genus in the Palæogene, especially Eocene, it is practically extinct in the Neogene.

ECONOMIC GEOLOGY OF THE PALÆOGENE (EOCENE AND OLIGOCENE).

1. Lime and Cement. The septarian concretions of the London Clay were formerly burnt for cement.

2. Building Stones. Not important. The bands of hard quartzite-conglomerate (Pudding Stone) of the Reading Beds and the irregular masses of hard sandstone ("sarsens") derived from the Reading and Lower Bagshot Beds have been used. They are often used in prehistoric stone-circles and dolmens. Bembridge Limestone is used locally (Isle of Wight).

3. Road Metal. Eocene gravels are largely quarried for paths, etc., where they occur.

4. Brick and Tile Clays.

a. Reading Beds—much used for tiles, etc., occasionally for fire-bricks.

b. London Clay, now less important than formerly as a brick clay. Used in the manufacture of Portland Cement (see page 273).

c. Lower Bagshot Beds. The quarrying of the fine light grey pipeclay is an important industry at Poole (Dorset). Used for sanitary earthenware, etc.

d. Barton Clay used locally.

5. Sands. Important.

a. Glass Sands. The upper part of the Thanet Sands of Charlton, Kent, is used for inferior bottle glass. The Barton Sands of the Isle of Wight are suitable, but little exploited.

b. Moulding Sands. The clayey lower part of the Thanet Sands of Charlton and Erith (Kent) furnishes a naturally bonded moulding sand of great value.

6. Lignite is important locally in the Bovey Tracey Basin.

7. Water. A small supply is obtained from the Thanet Sands in the synclinal basins, and naturally the alternation of clays and sands in the Eocene is conducive to the existence of small springs. Wells are sometimes sunk to the base of the Thanet Sand and into the Bullhead Bed. By washing away the matrix from the flints of the latter a semi-natural underground pool collects.

8. Soils and Scenery. The clay beds give rise to lowlands, much cultivated. Marshy in places (Essex). The sands are covered by heath-land or pine-forest (Bagshot Heaths of Surrey, Pine Forests of Bournemouth; also the great stretch of the New Forest).

CHAPTER XVII.

THE ALPINE EARTH-MOVEMENTS AND TERTIARY VULCANICITY.

There are no Miocene[1] sedimentary deposits in the British Isles, but the period was an eventful one in the history of this country, just as it was for the greater part of the world.

GEOGRAPHY AND HISTORY OF THE MIOCENE PERIOD.

1. The last great period of earth-movement was in the Carbo-Permian (Armorican or Hercynian Folding).

2. Various small movements during Jurassic times had followed principally previous lines of disturbance—especially Armorican and Charnian.

3. From the end of the Cretaceous and during early Tertiary times small movements had been going on—as we have noted in the case of the Weald. These movements were the opening stages of the great "Alpine Storm."

4. In Miocene times, practically the whole of Europe—in fact, the whole of the world—was convulsed by great orogenic movements. Most of the great mountain ranges of the world were built up about this time—the Atlas, Pyrenees, Alps, Carpathians, Caucasus, Himalayas, Rockies, Andes, etc.

5. Considering Europe alone, just as we have seen in previous cases of earth-movement, the folding cannot be definitely stated to belong to a single epoch. After the earlier tremors in Palæogene times, the first great period

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[1] Unless one assigns a Miocene age, as some palæontologists have done, to the Lenham and St. Erth Beds.

of movements seems to have been at the end of the Lower Miocene; to be renewed again in late Middle Miocene and Upper Miocene.

6. The Alps may be described as the Storm Centre for Europe. The mountains were built up by great thrusts and overfolds from the south.

7. As one moves northwards the folds become gentler, Great Britain is on the northern fringe of the area affected. The map, *Fig.* 67, shows the principal Tertiary fold ranges of Europe.

8. In England the folds are most marked in the south—there are even overthrusts from the south in Purbeck—and they become less marked northwards

9. It so happens that, in the South of England, the Alpine folds follow the same general direction—viz., east to west—as the Armorican folds, and have often been confused with them, or referred to as posthumous Armorican flexures. Some details of the principal folds will be given later.

10. The great Alpine movements were naturally accompanied by extensive igneous activity. We may note—

a. that the rocks directly associated with the folded regions belong to the Calcic or Pacific Suite;

b. that the rocks in intermediate regions or outside the main region of folding belong to the Alkaline or Atlantic Suite;

c. that the Brito-Icelandic Province is outside the main area of folding, and so is an alkaline province (see *Fig.* 67).

The igneous activity, like the folding itself, extended over very long periods. Thus, in the Brito-Icelandic Province, the earliest lavas may be of early Eocene age; in Iceland volcanic activity has not ceased yet.

11. Just as the principal mountain ranges are of Tertiary date, so most of the major features of the physical geography of the world were blocked out at the same time. The Hungarian Plain, the Black Sea and the Caspian Sea are but remnants of a great shallow sea—the Sarmatian Sea—which occupied a great basin between the fold ranges of late Miocene time.

12. The effect of these movements was that the

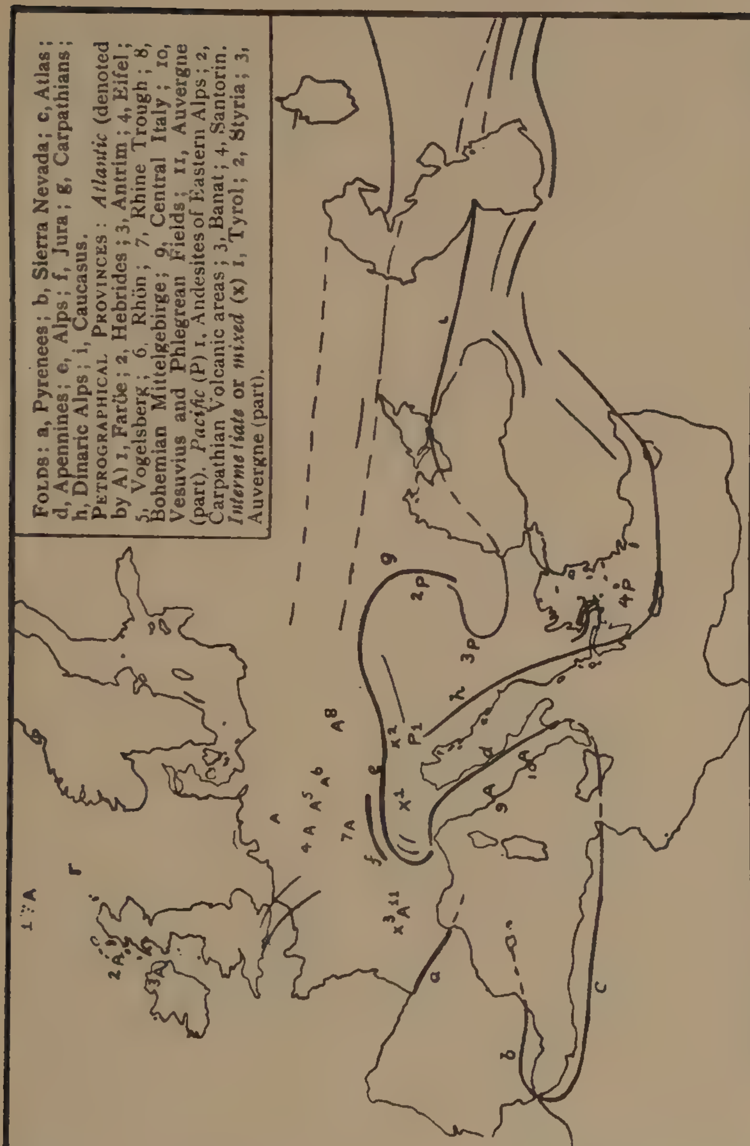

FIG. 67. Map showing the Tertiary (Alpine) Folds of Europe and some of the Tertiary Petrographical Provinces. (*L.D.S.*, after *Suess*.)

Notice the close association of the Pacific areas with lines of folding and the situation of the Atlantic areas outside the folded belts. A2, A3 and A7 are closely connected with faulting.

British Isles became land in Miocene times, the Oligocene Sea was driven to the south (Paris area) and to the north-east (Belgium and Holland were partly covered in Upper Miocene times). The Bolderian or Upper Miocene of Belgium has a fauna with a decidedly southern facies, and was probably connected with the Vienna Basin of Austria.

13. The drainage of England and of the greater part of Europe is post-Miocene. In this country it has been to a considerable extent modified by glacial interference during the great Ice Age (Pleistocene).

THE ALPINE FOLDING IN ENGLAND.

The most important series of flexures are—

1. Anticline of the Isle of Purbeck and Isle of Wight. The fold is very asymmetrical, the northern limb being so steep that it is frequently referred to as a monocline,[1] and is, indeed, a very good example of such a fold. Westwards, in the "Isle" of Purbeck, it passes into a thrust plane (thrust from the south). The Isle of Wight anticline is probably continuous with that of the Pays de Bray in France.

2. Synclines of the Hampshire "Basin," comprising more exactly—

a. Main syncline of the Hampshire Basin.
b. Portsdown anticline.
c. Salisbury-Chichester syncline.

3. Anticlines of the Wealden[2] Axis and the anticlines further west of the Vale of Wardour, the vales of Pewsey and Kingsclere.

4. Synclines of the London Basin.

The map, *Fig*. 68, shows these various folds. The horizontal sections, *Figs*. 69 to 71, should be carefully noted, as they also illustrate the succession in these areas.

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[1] It should be noticed that it has become the practice amongst American oil geologists to refer to evenly dipping strata as "monoclines" (="homoclines" of R. A. Daly).

[2] The Weald is variously described as an anticline or as an elongated dome or pericline. The latter is more correct since it pitches at both ends, but one must remember that it is complicated by minor folds within the main fold, as shown in *Fig*. 68.

Further north the effect of the Alpine movement was manifest in movements along old lines (*e.g.*, in S.E. Suffolk). Even at the present day earthquakes are associated with old Charnian lines of disturbance. The final uplift of the Pennine area may have taken place at this time.

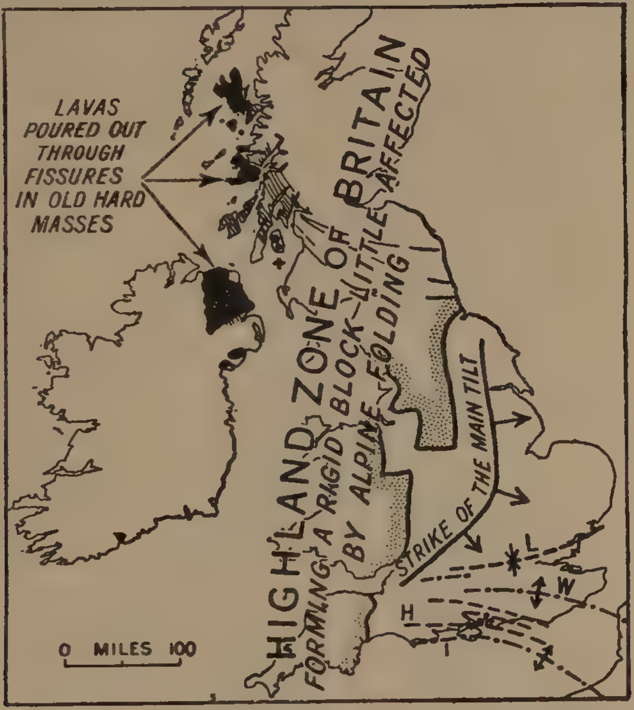


FIG. 67a. Map of the British Isles showing the effects of the Alpine earth movements. The arrows show prevalent dips. The fine black lines in the north are the igneous dykes of presumed Tertiary age (see p. 308).

(Reproduced from Stamp and Beaver's "The British Isles," by permission of Longmans, Green and Co., Ltd.)

THE POST-MIOCENE DRAINAGE OF ENGLAND (Selected Examples).

1. The Weald.

This is a classic example worked out by W. M. Davis.

a. One can picture the drainage of the Weald as having originated in late Miocene times. It was interrupted during early Pliocene times by the transgression of the Lenham-Beds Sea. We have some reason to believe that the Chalk was already denuded away from the crest of the fold at that time.

b. After the Miocene uplift of the Wealden axis, consequent streams flowing with the dip to north and to south from the axis of the fold would form the natural drainage.

c. These streams cut valleys in the chalk and reached the softer rocks (Gault clay) below. Some cut through and reached the Gault before others.

d Erosion of the Gault was rapid, and was hastened by subsequent streams—tributaries running along the strike into the main consequent streams.

e. The subsequent tributaries of those consequent streams which cut through the Chalk first beheaded those consequent

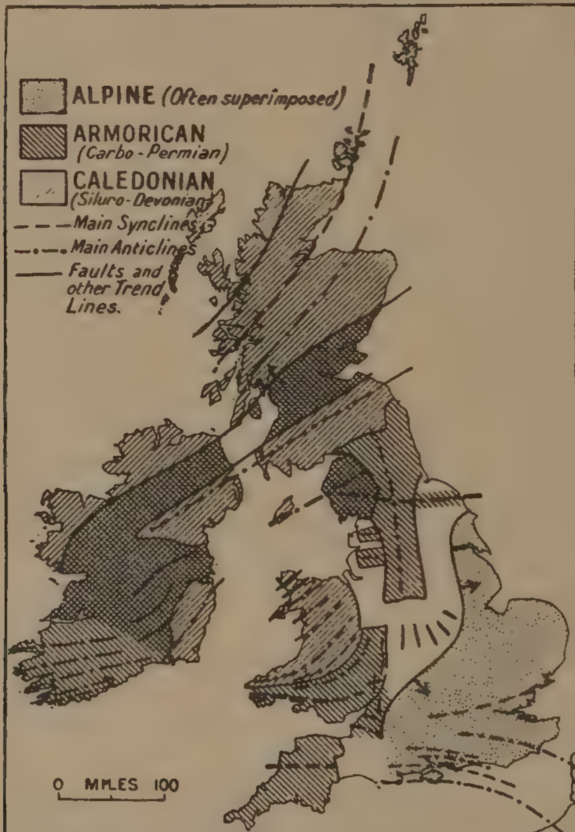


FIG. 67b. Morphological Map of the British Isles showing the spheres of influence of the main folding movement.

(Reproduced from Stamp and Beaver's "The British Isles," by permission of Longmans, Green and Co., Ltd.)

streams which had taken longer to cut through the Chalk. Some of the latter now rise on the Chalk (Cray), others have become dry (Dry Valleys and Wind-gaps of the North Downs).

f. This process of river capture was repeated when the consequent streams cut through the hard Lower Greensand Rocks on to the soft Weald Clays. It has been going on

FIG. 68. The Tertiary (Alpine) Folds of South-Eastern England. In the case of the London Syncline and the Wealden Anticline the main axes of folding are shown and also a few of the smaller folds within them. Only important faults are indicated. P, Pewsey Anticline; K, Kingsclere Anticline. (*L.D.S.*)

Since this map was drawn a special study of the minor structures of the London Basin has been made by Dr. S. W. Wooldridge (*Proc. Geol. Assoc.*, vol. xxxvii., 1926, pp. 162-196) and of the neighbouring Greensand belt by Dr. H. J. W. Brown. A map is reproduced giving the results of their work (see *Fig.* 79a).

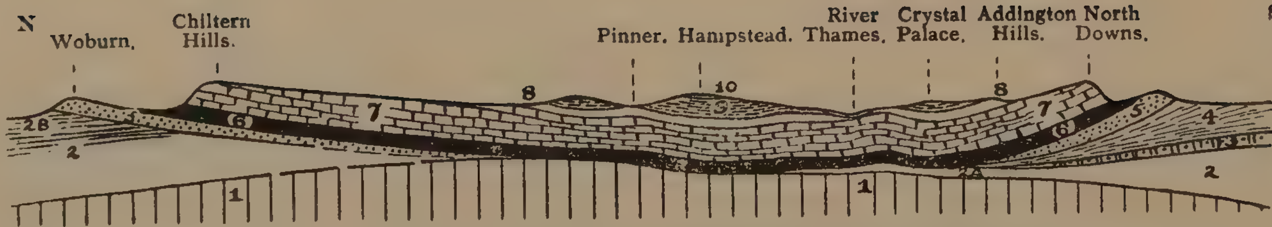


FIG. 69. Section across the London Syncline showing some of the minor folds. 1, The Palæozoic Platform 3, Various Jurassic Rocks including 2A, Bathonian Oolites. 2B, Oxford Clay. 3, Purbeck Beds. 4, Wealden. 5, Lower Greensand. 6, Gault. 7, Chalk. 8, Lower London Tertiaries (Landenian). 9, London Clay. 10, Bagshot Sands. Horizontal Scale, 12 miles = 1 inch. Vertical Scale, 4,000 feet = 1 inch. (*L.D.S.*)

FIG. 70. Generalized Section across the Weald Dome. 1, Palæozoic Platform; 2, Jurassic (various), including 2A (Lias) and 2B (Bathonian), also 3, Portlandian; 4, Purbeckian; 5, Wealden (including 5A, Ashdown Sands; 5B, Wadhurst Clay; 5C, Tunbridge Wells Sand); 6, Lower Greensand; 7, Gault; 8, Chalk; 9, Lower London Tertiaries (Landenian); and 10, London Clay. Horizontal Scale: 10 miles = 1 inch. Vertical Scale: 4,000 feet = 1 inch. The Wealden on the southern limb should have been shown almost as thick as on the northern. (*L.D.S.*)

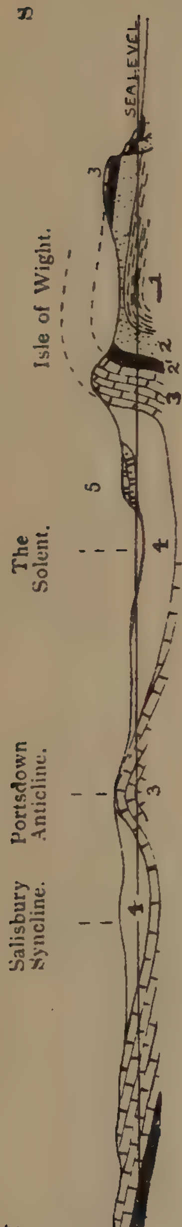


FIG. 71. Section across the Hampshire Syncline. 1, Wealden; 2, Lower Greensand; 2', Gault; 3, Chalk; 4, Eocene; 5, Oligocene. Horizontal Scale: 8 miles = 1 inch. Vertical Scale: 4,000 feet = 1 inch. (*L.D.S.*)

until the present day; it should be noticed that the breaching of the eastern end of the Weald by the sea at the Straits of Dover has interfered with the normal drainage, and allowed a subsequent stream (River Rother) to become of importance.

Some of these points are illustrated in the maps. (*Figs.* 72, 73 and 74.)

2. The Lake District.

Prof. J. E. Marr believes that the Lake District Palæozoic massif was originally covered by Jurassic and Cretaceous deposits, and that the present radial drainage was initiated on a dome-shaped uplift, the latter possibly due to a great laccolitic intrusion in Tertiary times.

THE TERTIARY IGNEOUS ROCKS.

During early Tertiary times the British Isles formed part of a great Petrographic Province — the Brito-Icelandic Province. Igneous action affected the greater part of the British area to a greater or less degree, but was most developed in the West of Scotland—especially in the Inner Hebrides (Skye, Rum and Mull)—and North-East Ireland.

The province affords a splendid example of the connexion between petrographical type and earth movement: the province considered as a whole is of one type, but special centres within the province are of a different type (see page 10).

1. Characteristics of the Whole Province (Regional).

The intrusion and extrusion are related to earth movements involving block faulting and differential subsidence over large areas. In other words, the igneous activity is associated with that type of earth-movement which is characteristic of the Atlantic type of coastline. The best example of the faulting is the great tract, including the Inner Hebrides, which has been let down between the Pre-Cambrian rocks of the Outer Hebrides on the west and the Pre-Cam-

brian rocks of the mainland on the east. The igneous rocks belong to the Atlantic or Alkaline suite, and consist, with but few exceptions, of basic types.

2. Characteristics of Special Centres (Local).

These centres are not only centres of local earth-movement—involving lateral thrust and folding of Pacific type—but also of more intense igneous activity. The rocks belong to the Pacific or Calcic Suite, and show a great range from ultra-basic to acid. The more important local centres are:—*a*. St. Kilda, *b*. Central Skye, *c*. Southern Rum, *d*. Ardnamurchan Peninsula, *e*. South-Eastern Mull, *f*. Arran, *g*. Mourne and Carlingford Districts of Ireland, *h*. ? Carrock Fell (Lake District).

The exact age of the igneous outbreaks cannot be fixed. The Irish lavas rest on the Chalk and the lavas (the earliest phase of activity) are therefore post-Cretaceous. The whole complex was profoundly eroded before Glacial times. Some sediments intercalated in the lavas yield a flora believed to be Eocene. It should be noted that the Alpine Folding in Central Europe reached its height in Miocene times. From analogy with other periods the Plutonic phase may have been developed at this period, but the Brito-Icelandic Province is too remote from the great regions of Alpine Folding for much weight to be placed on this comparison.

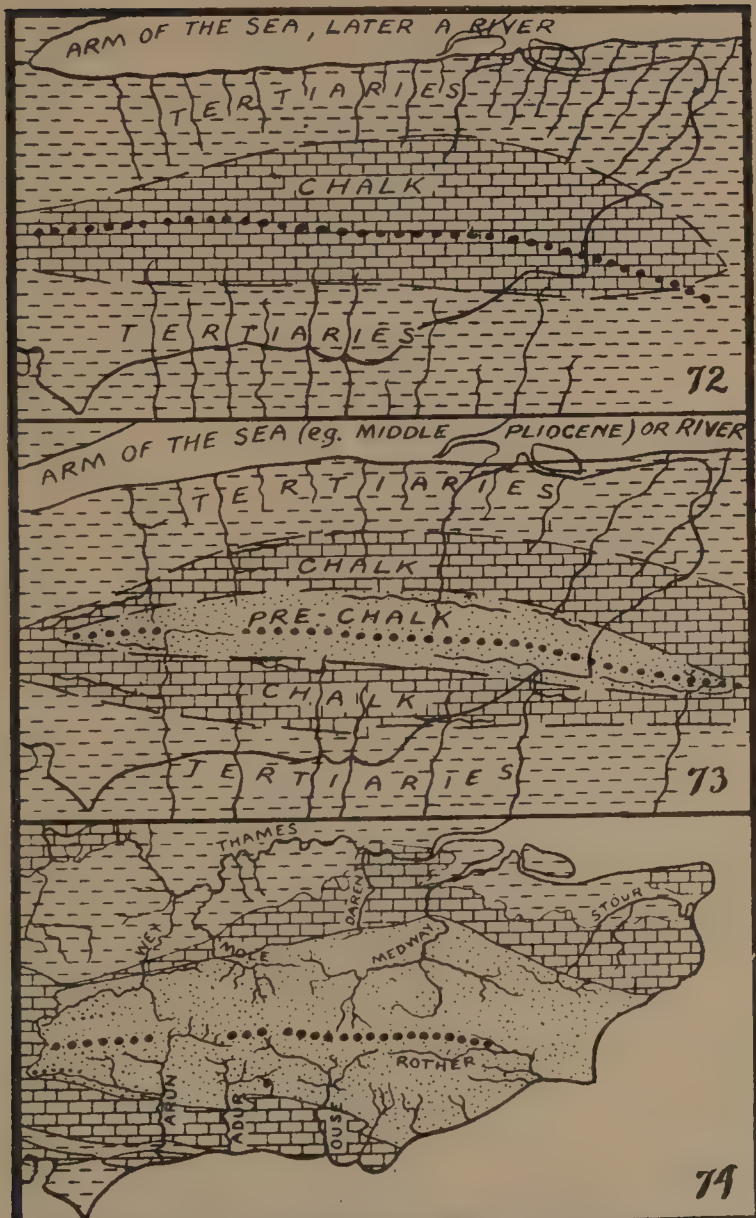
Three successive phases of activity occur:—

1 Volcanic.
2 Plutonic.
3 Minor Intrusions.

1. Volcanic Phase.

REGIONAL. Marked by the welling-up of huge quantities of Basaltic lavas, not from isolated centres, but from great fissures (Fissure eruptions). The great basalt plateaux which still remain are but remnants—faulted blocks—of a great lava field, which may have stretched from Ireland to Iceland. The eruptions were subaerial, and stream courses with fluviatile deposits (sometimes 300 feet in thickness) can be traced. Old land surfaces—marked by weathered upper surface of basalt flows and the resulting laterite—may also be seen (especially in Ireland), together with occasional lacustrine deposits with plant remains. Explosive action must have been rare, and ashes are exceptional. The lavas are mostly amygdaloidal olivine-basalts, rich in sodic minerals (natrolite, analcite, etc.).

LOCAL CENTRES. Before the great outburst of fissure eruptions ordinary crater volcanoes existed, and built up great cones of agglomerate and tuff. The necks are sometimes filled with plugs of basalt or with agglomerate. Later crater volcanoes seem to have broken through after the great fissure eruptions, and their necks, with plugs of trachyte and more acid rocks, pierce the basalts (Mull), whilst in at least one case a trachytic and rhyolitic group is intercalated in the basalts (Cuillin Hills, Skye).



FIGS. 72-74. Maps illustrating the evolution of the Wealden drainage. (*After W. M. Davis.*) 72, In late Miocene times, after the main uplift of the Anticline. Notice the consequent streams. 73. Pliocene times. The crest of the Anticline denuded away. 74, Present day.

2. Plutonic Phase.

Restricted to the special local centres enumerated above. The intrusions comprise—

a. Boss-like masses of fairly uniform character.

b. Laccolitic masses built up of successive sheet-like intrusions, often of different composition.

The order of intrusion was one of decreasing basicity; ultrabasic, basic and acid; invariably in that order.

a. *Ultrabasic* — peridotites, including almost pure olivine rocks (dunites) and olivine-anorthite rocks (allivalites). The eucrites (pyroxene and anorthite, with or without olivine) show a transition to the next group. A stratiform appearance of the intrusions is common, due to alternating olivine-rich and felspar-rich layers.

b. Basic—principally gabbros, with or without olivine. The Carrock Fell gabbro of the Lake District is possibly of this age, though an Ordovician age is now considered more likely.

c. Acid. The granites and granophyres were intruded but a short time after the earlier rocks, consequently marginal chilling is rare, but hybrid or mixture rocks, due to mutual reactions between the granites and the earlier basic rocks, are common.

3. Phase of Minor Intrusions.

REGIONAL. There are numerous sills, mostly of ophitic olivine-dolerite, sometimes more basic, and, on the whole, of distinctly sodic type.

The basic dykes, running in a N.W. direction, are a great feature of the Tertiary igneous cycle. Some of them are feeders of the lava flows, or of the sills, but the majority are later than the plutonic phase. They occur as far south as Anglesey and Durham. They are mostly dolerites (see *Fig*. 67a).

Less important and later in date are small sills and dykes of more acid composition—augite-andesite, trachyte and pitchstone.

A group of sodic dolerites occurs as sills and small laccolites in the Midlands of England—as at Rowley Regis, near Birmingham, and on Titterstone Clee Hill (Shropshire). They are possibly Tertiary, though Mr. R. W. Pocock has recently summarized the evidence for considering them late Carboniferous and of regarding the principal masses as extrusive. Mr. T. Robertson goes so far as to regard the Etruria Marls as owing their peculiar character to the inclusion of a large proportion of weathered basaltic rocks of similar age. (*Quart. Jour. Geol. Soc.*, vol. lxxxvii. (1931), pp. 1-29.)

LOCAL. Acid rocks—granophyre and quartz porphyry—occur in special areas. They are mostly later than the basic sills, but earlier than the regional faulting. Many of the basic rocks which occur cannot be separated from the regional group, but dykes become very abundant round some of the local centres. The inclined sheets of Skye and Ardnamurchan are of particular interest.

FIG. 75. Sketch-Maps showing the distribution of Tertiary Igneous Rocks in the British Isles. Inset Map: L, Lake District Centre (Carrock Fell), almost certainly Ordovician, but possibly Tertiary; M, Midland area, ? Tertiary; W, Wolf Rock. The main areas of volcanic rocks in Scotland and Ireland are indicated. (*L.D.S.*, in part after *A. Harker*.)

Recent work on the Tertiary Igneous Geology of the British Isles has been summarized by Dr. R. H. Rastall, *Geol. Mag.*, vol. lxviii., 1931, pp. 121-126.

Of outlying Tertiary igneous rocks, the phonolite of the Wolf Rock (Cornwall) and the ægirine-albite-quartz rock of Rockall, 190 miles west of St. Kilda, should be noted. The group of sodic dolerites, mainly intruded into Coal Measure Shales, and which occurs in the Midlands of England (see *Fig.* 75, inset) may be of Tertiary age, and has been mentioned above.

Economic—see page 325.

CHAPTER XVIII.

THE NEWER TERTIARY PERIOD.

NEOGENE PERIOD—MIOCENE.

As already stated, there are no sedimentary deposits in the British Isles which are definitely known to be of this age. The " Boxstones " of Suffolk and the Lenham Beds are claimed by some Palæontologists as Miocene; the Bovey Tracey Beds of Devonshire may be early Miocene, and some of the inter-basaltic fluviatile deposits of the West Coast of Scotland are possibly of this age.

On the Continent of Europe, in Southern Germany, Austria, etc., the upper part of the " Flysch "—a great thickness of sandstones and conglomerates—is Miocene in age. The effect of the Miocene Earth movements was in general the retreat of the sea in the north and its advance in the south. Many inland basins were cut off (Mainz Basin), some of which were freshwater, others marine at first, but later became freshwater (Vienna Basin). The great " Sarmatian Sea " has already been mentioned. The distribution of Miocene deposits strongly suggests that the present Mediterranean was cut off from the Indian region in Miocene times. In Germany the Miocene is truly marine only in the north-west, in the sheltered inland basins great deposits of lignite were laid down. There are extensive areas of igneous rocks of this age in Germany (Hesse and Lower Rhine), Czecho-Slovakia (Bohemia) and elsewhere.

NEOGENE PERIOD—PLIOCENE.

Undoubted Pliocene marine deposits *in situ* have limited distribution in England, only being found—

a. in East Anglia (Norfolk, and Essex);
b. as isolated patches along the North Downs of Kent and Surrey (Lenham Beds);
c. a small patch at St. Erth in Cornwall, and possibly sands at St. Agnes and St. Keverne.

For the purpose of a general account of the geography of the period, the old lithological classification may be used:

5. Chillesford, Weybourne and Cromer Beds.
4. Norwich Crag.
3. Red Crag.
2. Coralline Crag.
1. Lenham Beds.

GEOGRAPHY OF THE PLIOCENE.

Despite the comparatively recent date of formation of the Pliocene deposits, there are still many unsolved problems in connexion with them, and the reconstruction of the physical geography is a matter of considerable difficulty.

1. In the Miocene Period, South-Eastern England was affected by the Alpine movements and ridged up into a series of roughly east and west folds. The sea was thrown off from these ridges, and seems to have retreated right away from the British Area.

2. Towards the end of the Miocene Period, a general subsidence of South-Eastern England took place. The sea returned, coming from the north-east, and its erosive action gave rise to a plane of marine denudation. This plane can still be traced in England, and more easily in Belgium and Holland. It forms the platform on which the earlier Pliocene deposits were laid down.

3. Accordingly the earliest Pliocene deposits of England are found (now only as isolated patches) on the heights of the North Downs of Kent and Surrey. It is very doubtful, in fact quite improbable, that the Pliocene sea flowed right over the crest of the Wealden Anticline.[1]

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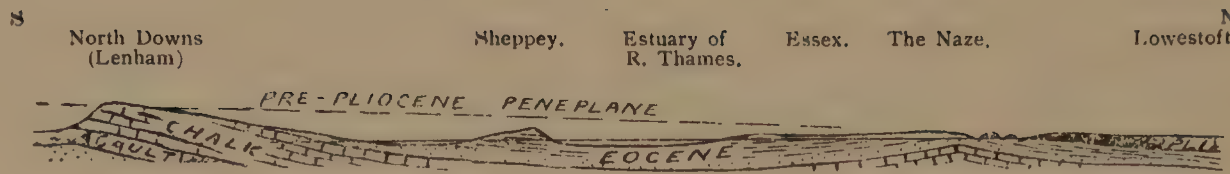
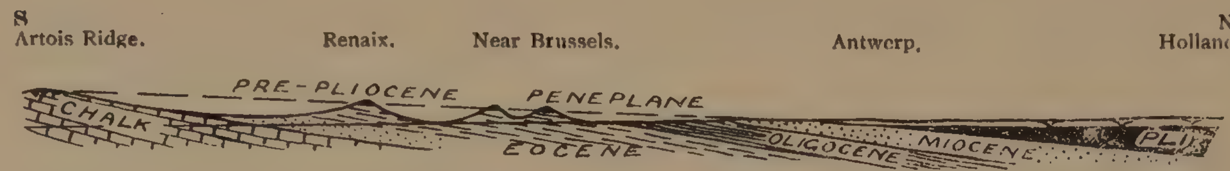
[1] Dr. S. W. Wooldridge, in an important paper, has succeeded in tracing the shore lines of the early Pliocene sea (The Pliocene History of the London Basin, *Proc. Geol. Assoc.*, vol. xxxviii., 1927, pp. 49-132). His results have been incorporated in *Figs.* 79b and 79c.





FIGS. 76-7. Diagrammatic Sections showing the Pre-Pliocene Peneplane in England (*Fig.* 76) and in Belgium and Holland (*Fig.* 77). Length of Sections roughly 100 and 120 miles respectively. Vertical Scale roughly 4,000 feet = 1 inch. (*L.D.S.*)

Detailed sections of the peneplane have now been given by S. W. Wooldridge (*Proc. Geol. Assoc.*, vol. xxxviii., 1927, pp. 49-132).

4. Just as the Alpine folding movements did not begin suddenly, but are to be traced from small movements from the end of the Cretaceous and right through the Palæogene; so they did not die away immediately. It appears that the Wealden Dome continued to rise even after the crest had been removed by the early Pliocene peneplanation. The result was that the plane was tilted—rising in the south and sinking in the north (*Figs.* 76 and 77).

5. As a natural result also the Pliocene sea retreated northwards, and, speaking generally, the East Anglian Pliocene deposits are the shallow water or coastal accumulations of the sea as it retreated, and so become successively newer northwards (*Figs.* 78 and 79). When the Diestian or Lenhamian Sea retreated from the London Basin, pebble beds largely of fluviatile origin seem to have been deposited and form the high level "Pebble Gravels" found mainly north of the Thames at an elevation of about 400 feet above sea level.

6. The fauna of the lower Pliocene deposits includes a large percentage of distinctly warm-water southern species. All these southern species are found in the little patch of Pliocene (of Coralline Crag age) at St. Erth, near Hayle, in Cornwall. Moreover, the earlier Crag deposits of East Anglia appear to have been accumulated under the influence of strong currents, probably coming from the south-west, and of easterly winds. Accordingly it seems certain that there must have been a channel connecting the sea of East Anglia with the sea in Cornwall (*Fig.* 79). Where did this channel run?

(i.) It is unlikely that it crossed the Wealden ridge directly.

(ii.) The Weald is a dome, or an anticline pitching at both ends, so that, whereas the early Pliocene sea which deposited the Lenham Beds may not have reached the main crest of the Wealden fold, it may well have passed round its western end and connected with the south-western sea in the English Channel. There is a patch of Pliocene in the Cotentin (on the coast of France opposite the Isle of Wight) which may indicate the extent of this bay of the Southern Sea. On the other hand, it seems unlikely that the sea would cross the great Isle of Wight fold, which is also of Miocene date.

(iii.) The Alpine movements threw Southern England into a series of east and west folds. The Channel may have

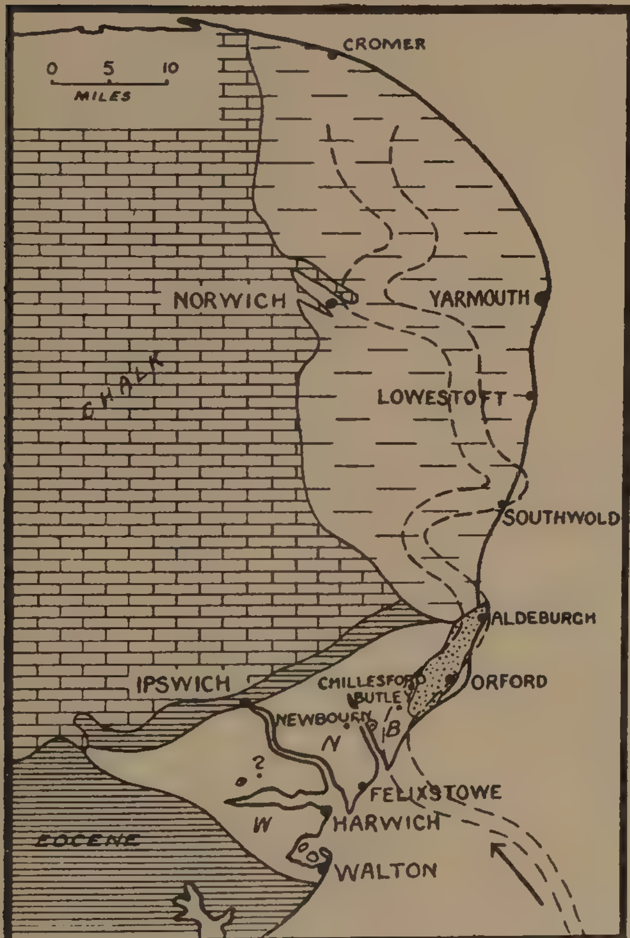


FIG. 78. The Pliocene Deposits of East Anglia. Dotted = Coralline Crag; Blank = Red Crag (W, Waltonian; N. Newbournian; B, Butleyan); interrupted lines = Norwich Crag and later deposits. The course of the "Chillesford River," probably a distributory of the Rhine, is indicated. (*L.D.S.*, adapted from *F. W. Harmer.*)

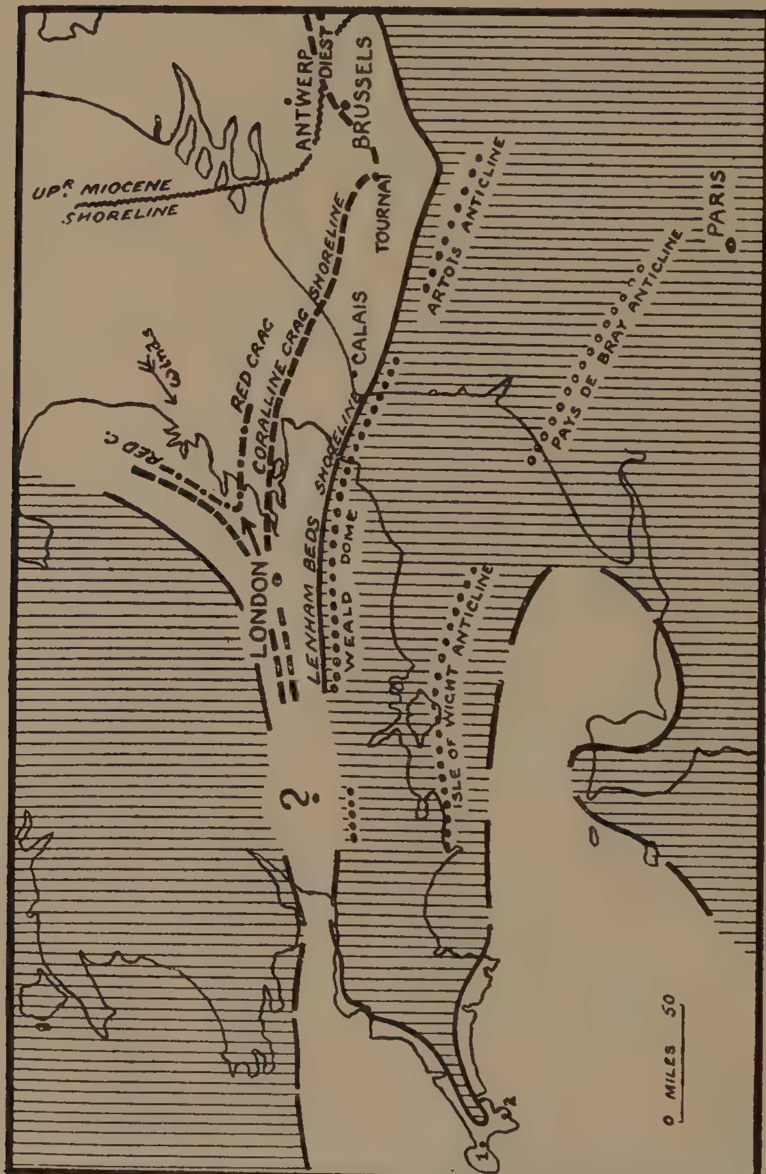


FIG. 79. The Geography of Early Pliocene Times. The land of earliest Pliocene (Lenhamian) times is shaded. The unbarbed arrow shows the direction of currents in the Coralline Sea. 1, St. Erth; 2, St. Keverne. (*L.D.S.*, in part after *F. W Harmer.*)

been along one of the synclinal folds, *e.g.*, the continuation of the London syncline into the Bristol Channel. Raised breaches of Pliocene age occur round the coast of Cornwall as far north as Bodmin and Boscastle. This seems the most probable explanation (see *Fig.* 79).

7. Wherever the channel ran, at a later date the connexion between the two seas was severed. At the same time a breach was effected between Scotland and Scandinavia, and communication opened with the Northern Ocean. Remains of Crag deposits occur off N.E. Scotland. The result is that from early Red Crag times the Pliocene faunas of the Anglo-Belgian Basin show a steadily decreasing percentage of southern forms.

With reference to migration of faunas in Pliocene times an interesting case may be quoted. The Lenham Beds are claimed by some palæontologists as Miocene. Some of the characteristic fossils—notably *Arca diluvii*—have a wide range in the Miocene of the Vienna Basin, and occur commonly in the Upper Miocene (Bolderian) of Belgium. It is suggested that such forms gradually migrated round from the Vienna Basin via Belgium, and did not reach Britain till earliest Pliocene times, and do not necessarily indicate a Miocene age for the deposits in which they occur.

8. Due to the continued uplift of the Weald and the tilting of the pre-Pliocene plane of erosion, the Pliocene deposits of Belgium and Holland thicken steadily northwards, and reach a very considerable thickness under Holland.

9. Towards the close of Pliocene time a change took place. The sea had been silted up and deltaic conditions ensued. The course of a great river (in which were deposited the Chillesford Beds) can be traced from south to north in East Anglia. It was probably one of the distributories of an enlarged River Rhine (*Fig.* 78).

10. It is difficult to separate the effects of climate from the effect of cold and warm marine currents, but, on the whole, the climate seems to have become steadily colder during the Pliocene.

THE PLIOCENE IN ENGLAND.

A. East Anglia.[1]

A more detailed classification of the English Pliocene is as follows :—

9.	Cromerian.	Cromer Forest Bed Series.	Freshwater and Estuarine
8.	Weybournian.	Weybourne Crag.	Marine.
7.	Chillesfordian.	Chillesford Clay and Sand.	Estuarine.
6.	Icenian.	Norwich Crag.	Marine.
5.	Butleyan.	Red Crag.	Marine.
4.	Newbournian.		
3.	Waltonian.		
2.	Gedgravian.	Coralline Crag.	Marine.
1.	Lenhamian.	Lenham Beds and Boxstone Fauna.	Marine.

Unfortunately all these terms are only of local (British) application. There is still a considerable discussion as to the classification and nomenclature of Belgian and Dutch Pliocene, and, beyond stating that the Diestian is generally considered to be equivalent to the Lenhamian, and that probably no Pliocene beds are present newer than Butleyan, it seems doubtful whether any useful purpose would be served by giving details of the Belgian-Dutch sequence.

1. LENHAMIAN.

a. Boxstone Fauna. At the base of the Coralline and Red Crags in East Anglia there is a conglomerate bed with numerous large pebbles of a brownish sandstone. They have been called " Boxstones " from the fact that a considerable proportion, when cracked open, have a cast of a fossil in the centre. The conglomerate also includes pebbles of various rocks, flints, jurassic fossils, bones of animals, etc. The box-stones have evidently been derived from some bed not now found *in situ* in England. The fauna includes various common Pliocene species and also some forms—such as *Conus dujardini*—characteristic of the Miocene or Older Pliocene of the Continent.

b. Lenham Beds. On the heights of the North Downs in Kent and Surrey, either resting on the old peneplane sloping to the north-north-east which truncates the Chalk (Turonian to Lower Senonian), or filling up solution hollows (" pipes ") at about the

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[1] F. W. Harmer, The Later Tertiary History of East Anglia, *Proc. Geol. Assoc.*, vol. xvii., 1902, p. 416; see also " Geology in the Field " and *Proc. Geol. Assoc.*, vol. xxxiii., 1922, pp. 285-305.

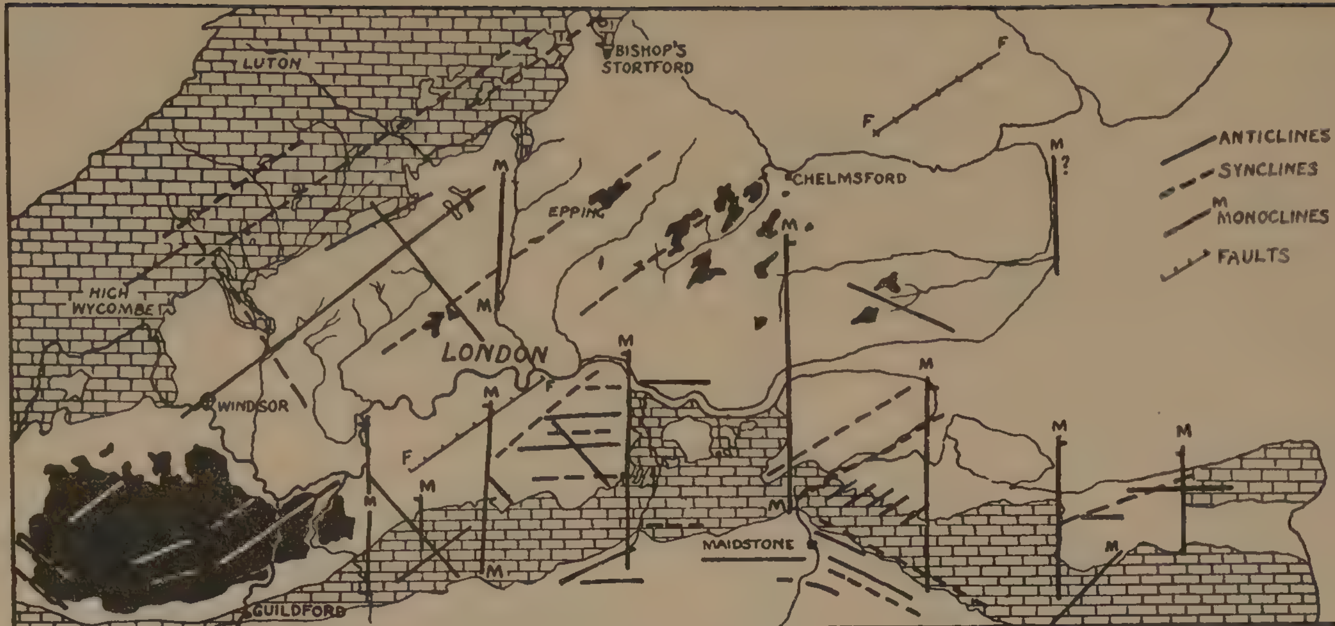

FIG. 70a. The Minor Structures of the London Basin, according to Dr. S. W. Wooldridge. This map demonstrates the importance of north-south monoclines of Alpine and post-Alpine age in determining the trend of present outcrops, stream courses and other physiographic features.
(See S. W. Wooldridge, The Structural Evolution of the London Basin, *Proc. Geol. Assoc.*, vol. xxxvii., 1926, pp. 162-196.)

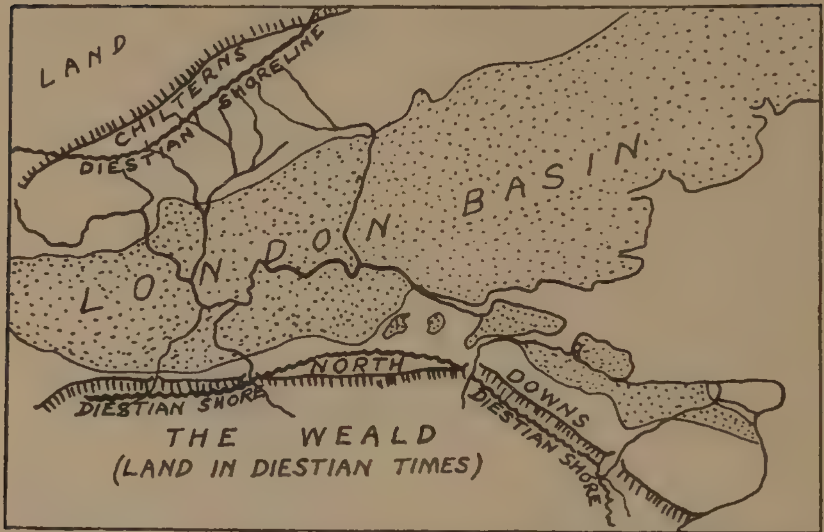

FIG. 79b. The geography of the London area in Diestian times, according to S. W. Wooldridge. The relationship of the Diestian shoreline to the present chalk escarpment should be noted.

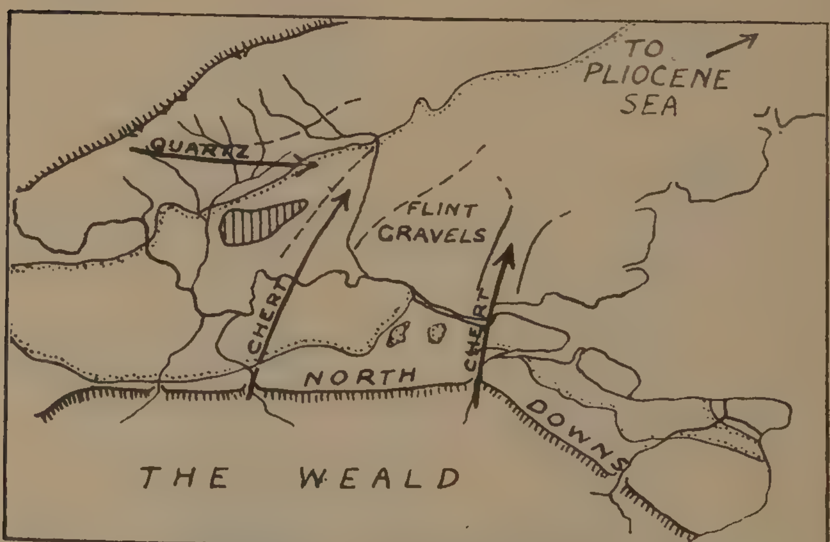

FIG. 79c. The geography of the London area in later Pliocene times according to S. W. Wooldridge. (The Pliocene History of the London Basin, *Proc. Geol. Assoc.*, vol. xxxviii., 1927, pp. 49-132.)

same level, there is a series of ferruginous, slightly glauconitic, sands, and flint gravels. Patches occur near Folkestone, from Folkestone to Maidstone at Harrietsham, Charing, Lenham, etc., They are generally unfossiliferous, but an extensive fauna occurs at Lenham. The fauna includes many common Coralline Crag species, with the addition of *Arca diluvii* (already mentioned), *Cardium papillosum*, etc. Apart from their position (*i.e.*, at about 600 feet above sea level along the crest of the North Downs) there is other evidence forthcoming as to the identity of age of these different patches of ferruginous sand. It is found that they have a characteristic assemblage of heavy mineral grains. Apart from the usual crystals and fragments of zircon, rutile, ilmenite, etc., which occur in all sands the Lenham Beds have monazite, large fragments of andalusite and staurolite.

If one projects the pre-Lenhamian peneplane to the north, it truncates the tops of certain hills, such as Shooter's Hill, and so there is some evidence for considering the gravels which cap those hills as Lenhamian in age. The presence of monazite supports this correlation.[1]

A similar series of patches of ferruginous sands (Diestian) is found capping the hills of French and Belgian Flanders. In the Boulonnais they rest on Chalk or Landenian, but to the north and east they rest on successively higher beds till they pass into the main mass of the Diestian, resting on Miocene, in the Belgian Campine.

2. Gedgravian (Coralline Crag).

The Coralline Crag consists of current bedded sands, largely made up of broken fragments of shells and bryozoa ("corallines" of older writers). It occurs as patches, surrounded by later Red Crag deposits, resting on an eroded surface of London Clay, and with the interesting nodule-bed, containing box-stones at the base. The actual area occupied by the Coralline Crag is quite small, but the fauna includes over 400 species of mollusca and 120 species of bryozoa. The fauna has a markedly southern facies, including such forms as *Voluta lamberti*, *Pyrula reticulata*, *Chama*, *Ovula*, etc., as well as *Cardita senilis*, *Terebratula grandis*, etc. Of the bryozoa the large *Fascicularia* and *Cellepora* are important. The Coralline Crag appears to have been accumulated on the floor of a shallow sea, under the influence of strong currents.

3-5. Waltonian, Newbournian and Butleyan (Red Crag).

The Reg Crag covers a larger area than the Coralline Crag, but is often obscured by glacial deposits. It wraps round the "islands" of Coralline Crag, and rests on London Clay, Reading Beds or Chalk (*Fig.* 80). The beds as a whole consist of shelly, ferruginous sands, and were deposited as shallow-water or coastal

[1] But reference should be made to the recent work of the Geological Survey. See memoirs on the Guildford and Reigate Sheets.

deposits during the northward retreat of the Pliocene sea. Consequently deposits of the various ages into which the Red Crag has been divided do not occur in regular superposition, but have an imbricate arrangement, the oldest in the south and the youngest in the north.

a. Waltonian. Two stages have been separated. The older, or Walton Crag of Essex, is characterized by *Neptunea contraria.* The newer or Oakley Crag, with *Mactra obtruncata* as characteristic, has a group of northern species (*Astarte, Scalaria groenlandica, Trophon islandicus*) amongst its fauna.

b. Newbournian, with *Mactra constricta*, occurs further north, and shows a great increase in the number of northern mollusca, whilst southern forms are comparatively scarce. There is possibly a fauna intermediate between those of Oakley and Newbourne, but no exposure occurs in the neighbourhood of Bentley, where it might be found.

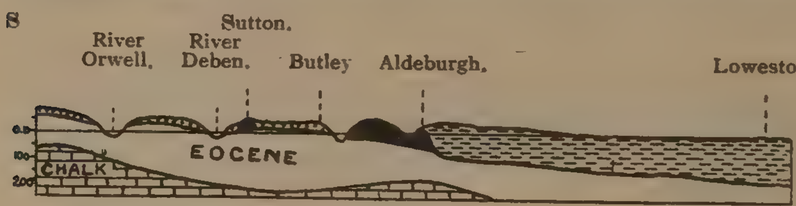

FIG. 80. Section through the Pliocene deposits of East Anglia. In black, Coralline Crag; dotted, Red Crag; interrupted lines, Norwich Crag. (*L.D.S.*, adapted from *F. W. Harmer.*)

c. Butleyan, or Butley Crag, with *Cardium groenlandicum*, occurs yet farther north. Cold-water species are still more numerous. The most abundant fossils include *Tellina obliqua, T. prætenuis, Mactra constricta* and *Cardium angustatum.*

6. ICENIAN (NORWICH CRAG).

The Norwich Crag occurs to the north of the Red and Coralline Crags, and occupies a much larger area. It comprises sands, gravels and clays, with a fauna consisting very largely of existing species. Extinct or southern forms are rare, whilst cold-water or even arctic species, not present in the Red Crag, appear (*Astarte borealis, Mactra subtruncata*, etc.). At the base is a conglomeratic bed, with numerous mammalian remains, including *Elephas antiquus, Mastodon arvernensis*, etc.

7. CHILLESFORDIAN (CHILLESFORD BEDS).

These beds comprise micaceous sands overlain by estuarine clay, and they can be traced as a sinuous band from Walton in Essex to the north of Norfolk, reposing indifferently on older Pliocene deposits. Fossils include *Cardium edule, Mya truncata* and *Mactra ovalis.*

8. WEYBOURNIAN (WEYBOURNE CRAG).

The Weybourne Crag overlies the Chillesford Beds in Suffolk, and comprises sandy clay and fine-grained micaceous sands, with *Purpura lapillus* and *Buccinum undatum*. Further north are more argillaceous deposits, with a marine fauna, including about 20 per cent. of distinctly arctic forms (*Astarte borealis*, *Cyprina islandica*, *Saxicava arctica*).

9. CROMERIAN (CROMER BEDS).

These beds comprise—

c. Upper Freshwater Bed — clay, with plants and non-marine mollusca.

b. Forest Bed—estuarine clays, with gravels and sands. Masses of peat, roots and branches of trees, mammalian remains, etc.

a. Lower Freshwater Bed—green sandy clays, with plant remains.

The overlying Arctic Freshwater Bed is usually classed as Pleistocene.

The majority of plants and non-marine mollusca in the Cromer Beds are still living, but of the 60 mammals many are extinct (*Machærodus*, *Ursus spelæus*, *Rhinoceros etruscus*, *Elephas antiquus* and *E. meridionalis*)

B. Cornwall.

The St. Erth Beds[1] form small patches on the isthmus to the east of the Land's End Granite Mass, resting on Palæozoic slates. The fauna includes most of the southern forms characteristic of the Coralline, or of the lower part of the Red Crag of East Anglia, but the northern and arctic species of the latter are absent. Raised beaches and coast-lines of this or earlier age occur along the Cornish coasts, varying in height from 370 feet at St. Agnes Beacon to 750 and 1,000 feet near Camelford and Bodmin.[2] The heavy mineral assemblage would seem to connect patches of sand at St. Keverne (Lizard District) and St. Agnes with the St. Erth deposit.[3]

C. Cave and Fissure Deposits.

Bones of *Elephas meridionalis* and *E. antiquus* have been found in a trench-like hollow in chalk at Dewlish in Dorset.

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[1] Claimed as Miocene by some palæontologists.

[2] An extensive literature now exists concerning the character and origin of the various platforms. See W. V. G. Balchin, *Geog. Jour.*, 118, 1952, pp. 453-476.

[3] H. B. Milner, The Nature and Origin of the Pliocene deposits of the county of Cornwall. *Quart. Journ. Geol. Soc.*, vol. lxxviii., 1922, 348-377.

A fissure in Carboniferous Limestone near Buxton in Derbyshire yielded bones of *E. meridionalis, Mastodon arvernensis* and *Rhinoceros etruscus.*

It should be noted that masses of high-level Pliocene deposits, containing recognizable fossils, have been found in recent years at Netley Heath, Surrey, and Rothamsted, Herts. At the former locality the fauna suggests correlation with the Red Crag. All such deposits must, in a general way, be grouped with the so-called "Lenhamian" in view of their physiographic position—but it will be seen that some doubt must exist as to their actual age.

THE PLIOCENE OF THE CONTINENT OF EUROPE.

There was a general retreat of the sea throughout Europe. In the South of Europe the Pliocene is mainly marine in Spain, Algeria, Italy and Greece, and the fauna is very like that of the Mediterranean of the present day. The great Sarmatian Sea of Miocene times had become divided up into separate basins, though of greater extent than at the present day. In Germany the Pliocene is fluviatile. From the Atlantic Ocean there were various bays covering parts of France and extending at least a considerable distance up the English Channel.

LIFE OF THE PERIOD (NEOGENE).

The life of the Neogene Period is marked by the rapid evolution of the mammals; the gradual replacement of the southern marine molluscs by colder-water types from the north and the increasingly temperate character of the flora.

a. Plants. The flora of the Lower Miocene is still sub-tropical, becoming more temperate in higher beds. *Magnolia* occurs as far north as Spitsbergen, but other northern floras of Miocene age—*e.g.*, Japan—have quite a temperate aspect.

b. Vertebrata. There is a sudden appearance of great Proboscideans—the ancestors of the Elephant—in Europe (*Dinotherium* and *Mastodon*, but *not Elephas* in Miocene; *Dinotherium, Mastodon*, and, later, *Elephas—E. meridionalis* and *E. antiquus* — in Pliocene). The oldest Felidæ (*Machærodus,* the Sabre-toothed Tiger), as well as the first antlered deer and the earliest ape. appear in the Miocene, whilst the horse-like *Hippotherium* and numerous Rhinoceroses are characteristic of the Pliocene.

c. Mollusca. As in the Palæogene, but northern forms become more abundant. The Molluscan faunas of the Miocene and Pliocene can be divided into—

(a) Extinct species.

(b) Warm-water species still surviving in more southern latitudes.

(c) Cold-water species still surviving in northern latitudes.

Members of the latter group—such as *Cyprina islandica* and *Panopæa norvegica*—spread even as far south as the Mediterranean.

d. Polyzoa. Important in the Coralline Crag.

e. Echinodermata. Certain genera of Irregular Echinoids, which had survived from the Cretaceous, become extinct.

f. Protozoa. Nummulites becomes practically extinct.

ECONOMIC GEOLOGY OF THE NEOGENE (SEDIMENTARY).

1. Road Metal. The pebble beds were much used locally for this purpose, notably the boxstones. The shelly sands of the Coralline Crag were a favourite material for garden paths.

2. Phosphates. Phosphatic nodules and phosphatized bones from the conglomerates were formerly used in the manufacture of artificial manure.

3. Sands. The Pliocene Beds at St. Erth (Cornwall) yield a naturally bonded moulding sand, the "Cornish Red" of commerce. An inferior quality is known as "Cornish Yellow."

4. Agriculture. The shelly sands are extensively dug for "marling" heavy clay soils.

The economic value of the Tertiary Igneous Rocks should also be noticed.

Some important building stones are furnished by the granites of the Mourne and Carlingford Districts of Ireland and of the Cuillin Hills, Skye. Some of the basalts are beautifully columnar (as at the celebrated localities of Giant's Causeway and Staffa), and the stone has been employed in harbour work. The columns are carefully removed and individually numbered, and are then built in with cement in the same relative position in harbour breakwaters, etc. The well jointed Carboniferous basalts of the Midland Valley are used in the same way. Of great importance are the igneous rocks of the Midlands of England as road stones (see also page 308).

CHAPTER XIX.

THE QUATERNARY PERIOD.

The Quaternary Period[1] comprises all the time which has elapsed from the end of the Pliocene Period until the present day. One can refer to it as the Age of Man, and it was formerly defined by the presence of human remains, that is to say, the opening of the Quaternary Period was believed to be marked by the appearance of man. We now know, however, that man or his ancestors were in existence at an earlier date, and the Quaternary Period must be redefined more precisely. Two divisions of the Quaternary Period are usually recognized.

2. Recent or Holocene.
1. Pleistocene.

In England many extinct species of mammals and mollusca occur in the lower but not in the upper division.

The deposits and phenomena of the period are very numerous and varied, but often very difficult to study on account of their local character. Perhaps of all the divisions of geological time, it is most difficult to give a general account of the Quaternary.

We will start by outlining a general history of the British Isles since Pliocene times, and then proceed to a more detailed account of certain groups of phenomena, attempting at the same time to reconcile the varied facts recorded.

GENERAL HISTORY OF THE QUATERNARY PERIOD.

1. We have already noticed the increase in the number of cold-water or boreal molluscs in late Pliocene times.

[1] A good general account is given by W. B. Wright, "The Quaternary Ice Age," 2nd Ed., 1936. The literature relating to Quaternary deposits is enormous. An invaluable summary of the present state of knowledge was prepared by P. G. H. Boswell, Presidential Address to Section C, British Association, York, 1932. His chronological table is summarized on pp. 350a and 350b.

With the opening of the Pleistocene both fauna and flora begin to assume a definitely arctic character.

2. A period of intense cold then ensued — usually known as *the* Glacial Period or the Great Ice Age. The greater part of the British Isles north of a line from Bristol to the mouth of the Thames, as well as the northern part of the Continent of Europe, came under the influence of Ice action. The Glaciers of Central Europe —especially the Alps—were much more extensive than at present. Similar phenomena are seen in Northern Asia and in North America, so that the whole of the Northern Hemisphere at least felt the effects of a period of intense cold.

3. The cold period does not seem to have been continuous. There were one or more periods — the Interglacial Periods—during which the cold became less intense and the glaciers retreated.

4. As a belt circling the North Pole there was a number of Ice-Caps, similar to that which covers most of Greenland at the present day, and the various ice-caps or ice-centres waxed and waned in relative importance. In this way the same district was sometimes affected by ice from one centre, sometimes by ice from another centre.

5. Finally, conditions were ameliorated and the ice retreated. It left in its wake not only great stretches of purely glacial deposits (boulder clay), but the waters derived from the melting of the ice gave rise to torrents spreading over the still frozen ground and depositing great fans of gravel and sand.

6. After the retreat of the ice, a broad tract of cold desert encircled the Northern Hemisphere. Here conditions resembled to some extent those in the Tundra or Cold Deserts of Siberia at the present day. The fauna was similar, almost identical, and under the influence of strong desert winds great clouds of fine dust swept across the Continents of Europe, Asia and North America, and were deposited as a mantle of loess. Loess formation still goes on in the interior of Asia.

7. As the cold continued to become less severe the belt of Tundra became a belt of dry grass land or Steppe, inhabited by the same animals that one finds in the Steppe Lands of Eur-Asia at the present day. Soon humidity

increased and forests sprang up and clothed the greater part of the Continent of Europe north of the Mediterranean Region. We are still living in this Forest Period, though man has largely cleared the forest-lands.

8. Some geologists, then, divide the Quaternary Age into three periods:

a. Forest Period.
b. Tundra and Steppe Period.
c. Glacial Period.

9. It follows naturally that the Ice-Sheets were the controlling factors in Pleistocene times. Very few animals or plants, if any, could live in the regions actually covered by ice, in consequence the glacial deposits are devoid of fossils. Round the margins of the ice extensive faunas and floras existed, they migrated under the influence of fluctuations in the intensity of the cold. One finds thus two sets of Pleistocene deposits—

a. Glacial deposits without fossils.
b. Contemporary extra-glacial deposits with fossils and indications of the presence of man (artefacts or implements, etc.).

The great problems of Quaternary geology centre around the correlation of the two sets of deposits, and of the sequence of events they indicate.

THE GLACIATION OF EUROPE—GENERAL.

1. The principal centre of ice accumulation in Europe was Scandinavia. Probably the ice first formed along the main mountain ridge of the Peninsula, whereas later as snow and ice collected the centre of the ice-cap shifted eastwards over the Gulf of Finland or the northern part of the Baltic Sea. It would seem that the ice reached a thickness of well over 10,000 feet. From there great glaciers or ice-sheets radiated in all directions. One, to some extent comparable with the Ross Barrier Ice-Sheet of the Antarctic which floats on the Ross Sea, stretched right across the North Sea and impinged on the British Isles.

2. At a slightly later date a number of small ice-caps originated on the various highland regions of the British Isles, and became sufficiently powerful to push back the

Scandinavian Ice and prevent it from actually touching British shores.

3. The Alps formed an independent centre of ice dispersion.

THE GLACIATION OF THE BRITISH ISLES.

1. Evidence of a Former Widespread Glaciation.

1. Deposits (often collectively known as "Drift").[1]

a. **Boulder Clay.** This is the most typical glacial deposit. It consists of angular and scratched and roughly smoothed boulders of various rocks, and varying greatly in size, irregularly scattered in a matrix of "clay." The "clay" differs from ordinary china or sedimentary clays (which consist principally of a hydrated aluminium silicate) in consisting of ground up, largely unaltered rock. Boulder Clay varies greatly in composition, largely with the nature of the underlying rocks. Thus red sandstone is often covered by red, sandy boulder clay, whilst great spreads of whitish "Chalky Boulder Clay" cover areas of chalk. The materials of the Boulder Clay are, then, largely of local origin, but amongst the stones are boulders of far-travelled rocks or erratics. Some of these erratics can be matched with rocks still *in situ*, and the direction of flow of the ice thus determined. Boulders of Scandinavian igneous rocks occur in the Boulder Clay of the Eastern Counties of England, whilst fragments of the Shap Granite can be traced from the Lake District across into Northumberland and Durham. Boulder Clay occurs principally on low ground, and tends to tail off against hills. Till or Tillite is another name for Boulder Clay, but is sometimes restricted to Boulder Clay which has become indurated.

b. **Sands and Gravels.** Interbedded with the Boulder Clay or overlying it are irregular beds of current-bedded or stratified sands and gravels deposited by streams flowing from the glaciers, or during a temporary retreat of the ice.

c. **Moraines.** Accumulations of boulders sometimes occur. One finds the various types which are associated with glaciers at the present day. On the Continent of Europe a well-marked Terminal Moraine marks one stage in the retreat of the ice, and is well seen in Schleswig and Northern Germany. Various terminal moraines occur also in the British Isles.

d. **Perched Blocks** are isolated boulders of foreign rock left stranded on valley sides by the melting of the valley glacier on the surface of which they were being carried.

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[1] The term "Drift" is often loosely but conveniently used to include all superficial deposits. The "Drift" Maps published by the Geological Survey show these beds, whereas the "Solid" Maps do not.

e. **Drumlins** are lenticular or irregular mounds of moraine-material, usually part of a terminal moraine.

f. **Outwash Fans** are spreads of sands and gravel deposited by waters resulting from the melting of the ice.

g. **Eskers** are curious, long sinuous banks of sand, etc.

(i) They may mark stages in the retreat of a glacier.

(ii.) They may mark the courses of subglacial streams.

The ice, therefore, moved approximately at right angles or approximately parallel to the length of the esker, according to which view is adopted.

2. Other Evidence of Glaciation.

a. **U-shaped valleys** with hanging lateral valleys.

b. **Corries** or **cirques** and arêtes.

c. **Roches moutonnées.**

d. **Polished rocks** and **ice-scratches.** "Nail-head" scratches show direction of flow of the ice.

e. **Crag and tail** structure.

f. **Glacial Lakes**—basins either scooped out by ice-action or lakes dammed by moraine.

g. **Parallel Roads** of Glen Roy (compare beaches surrounding Lake Bonneville in the United States). They are successive shorelines of an ice-dammed lake.

For definitions and further details the reader is referred to any text-book of Physical Geology.

II. The Ice Centres in the British Isles.

The accompanying map (*Fig.* 81) shows the main Centres of ice-dispersion in the British Isles. They are—

1. SCOTLAND.
   a. North-West Highlands.
   b. Central Highlands (Grampians).
   c. Southern Uplands.
   Other local transient centres in Skye and Mull.
2. IRELAND.
   a. Northern Ireland.
   b. Western Ireland.
   Other local centres.
3. ENGLAND.
   a. Lake District.
   b. North Wales.
   c. Central Wales.
   d. Southern Pennines.
   England was powerfully affected also by
   e. "Irish Sea Ice"—derived from Northern Ireland, Southern Uplands and Lake District, and Coast of Wales, and
4. THE SCANDINAVIAN ICE-SHEET or "North Sea Ice."

III. The Glacial History of Different Parts of the British Isles and the Glacial Deposits.

As stated above, the different centres of ice-dispersion were not all operative at the same time, and the history of the different regions of the British Isles accordingly differs from place to place.

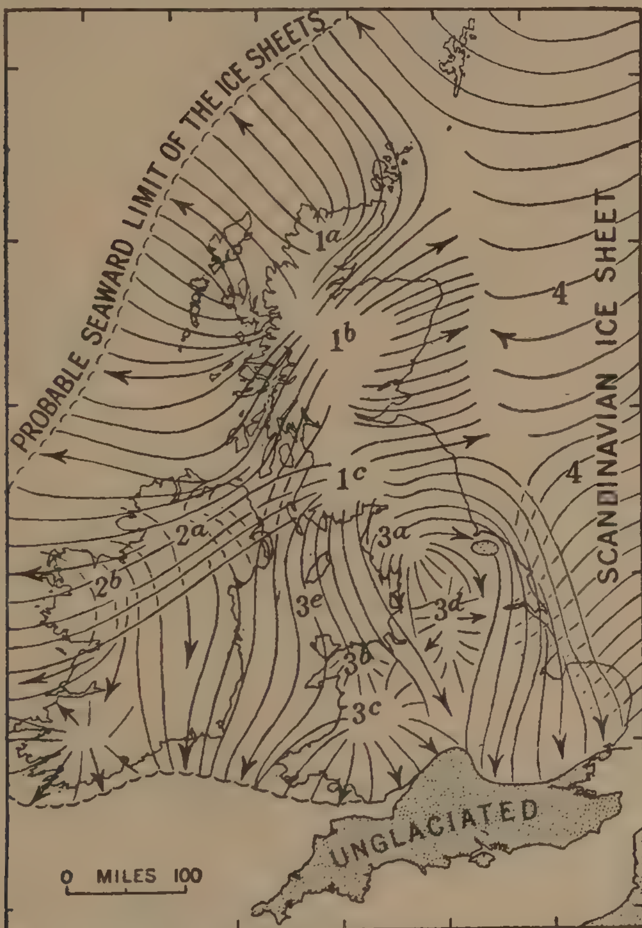

FIG. 81. Map illustrating the Glaciation of the British Isles. Centres of dispersion numbered as on page 330. Earlier movements shown by interrupted lines, later movements by continuous lines. Directions of flow are generalized. (*L.D.S.*)

(Reproduced from Stamp and Beaver's "The British Isles," by permission of Longmans, Green and Co., Ltd.)

1. The Highlands of Scotland. The ice moved outwards from the main centres of dispersion. To the east it was blocked by the Scandinavian ice and forced to turn northwards, to the west it was free to move out into the Atlantic. Most of the Scottish Glens show marked glacial features—long straight valleys, glacial lakes, etc. The deposits are divisible into—

b. Upper Boulder Clay with sands and gravels.
a. Lower Boulder Clay or Till.

The Boulder Clays may reach over 100 feet in thickness, especially on low ground; they tail off against the hills, but may be found up to 1,600 feet above sea-level. They consist mainly of local material. The "Till" is a hard rock comparatively speaking. Round the coast the Upper Boulder Clay is often covered by shell-bearing sands, to which reference will be made later (see page 333). The final retreat of the glaciers is marked by terminal moraines in many of the Highland Glens.

2. The Southern Uplands of Scotland and the Lake District of England.

Three centres of dispersal may perhaps be distinguished—

a. Granite Hills of Galloway. Flow of Ice to the north from the Southern Uplands was small. It joined with the Highlands Ice and flowed eastwards; from the Galloway Centre ice flowed southwards into the Irish Sea and Lancashire, and westwards into Ireland.

b. Lake District. The ice flowed—

(i) Down the valley of the Lune.
(ii.) Down Ribblesdale past Ingleborough.
(iii) Across the Pennines into Northumberland.

c. Cheviot Hills. The ice joined the (iii.) branch of the Lake District Ice.

Most of the area formerly covered by these ice-sheets has a mantle of Boulder Clay or "drift," very like the "Till" of Scotland. Local material predominates in the drift.

3. North of England (East of the Pennines).

a. The Coasts of Yorkshire (and possibly of Lincolnshire) seem to have come, first of all, under the influence of the Scandinavian Ice Sheet (or North Sea Ice), as the lowest or "Basement Boulder Clay" has erratics of Scandinavian igneous rocks. It rests on an old buried cliff and beach deposits, to which reference will be made later. The Basement Boulder Clay has contorted patches of sand with marine shells (*Astarte borealis*, etc.), many of which do not now live in British waters.

b. Later the ice-stream from the Lake District and South Scotland flowed down as far as North Yorkshire (Cleveland Hills) and then divided.

(i.) Western branch flowed down the Vale of York and gave rise to a confused mass of deposits. There are two fine terminal moraines near York.

(ii.) Eastern branch followed the coast or moved partly over the sea and impinged on the coast of Holderness and Lincolnshire. It deposited the "Purple Boulder Clay" with

erratics of Shap Granite and various northern rocks. Continuing to move inland, it crossed the chalk hills of the Lincolnshire Wolds, and to the west of those hills the Boulder Clay is very calcareous, and contains much chalk (Chalky Boulder Clay).

c. Slightly later the bulk of the ice seems to have come direct from the Southern Uplands via Northumberland, and Shap erratics become scarce in this higher or Hessle Boulder Clay, and boulders of all sorts are smaller. There are often sands, etc., between the Purple and Hessle Boulder Clays. Some of the patches of sand and gravel occurring between or associated with the boulder clays have remains of marine shells. The shells are often crushed and broken, at other times apparently undisturbed and in position of life, and occurring in beds of undisturbed sand. Such fossiliferous deposits not only occur on the East Coast, but also at considerable heights above sea-level in North Wales and elsewhere.

Their origin is a matter of some dispute. Two principal explanations are possible—

(i.) that they are marine deposits *in situ*, and that the whole of England was depressed some 500 or 600 feet and largely covered by sea, and that the boulder clay is a submarine deposit. This is very unlikely.

(ii.) that in some way masses of sediment have been pushed up on to the land by the ice sheets. The broken character of some of the shells corroborates this suggestion, but it has been difficult to explain the undisturbed deposits. From observations in the Antarctic we now know that portions of the sea-bottom may become frozen on to the lower surface of an ice-sheet floating over a shallow sea (*e.g.*, Ross's Sea), and that summer melting of the surface of the sheet may cause such a frozen mass to be lifted off the sea bottom. Imagine what would happen if the whole ice-sheet was then pushed on to the land and then melted The frozen mass of the sea bottom would then be deposited gently and practically undisturbed on the surface of the land.

4. East Anglia.[1]

a. Like Yorkshire, East Anglia first came under the influence of the Scandinavian Ice-Sheet or North Sea Ice. The Boulder Clay (best known as the North Sea Drift) belonging to this period has numerous boulders of Scandinavian rocks (Rhomb-porphyry, Nepheline Syenite, etc., from the South of Norway). The effect of this ice-sheet impinging on the coast was to "ruck up" the surface of the Chalk and to shear off great masses sometimes nearly

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[1] This section stands as originally written. Recent work has made considerable alterations to the succession and its interpretation. See P. G. H. Boswell, "The Stratigraphy of the Glacial Deposits of East Anglia in Relation to Early Man." *Proc. Geol. Assoc.*, xlii., 1931, pp. 87-109, and table on pp. 350a-b.

a quarter of a mile in length. The lowest beds of boulder clay which had already been deposited are tremendously contorted, and have wisps and streaks of sand, etc. (Cromer Till below, Contorted Drift above). As one might expect, the North Sea Drift tails off inland. The sands and gravels occurring as irregular beds between the North Sea Drift and the Chalky Boulder Clay are the "Middle Glacial Gravels."

b. East Anglia was then invaded by a great sheet of land ice which deposited the Chalky Boulder Clay. The ice which had swept across the Lincolnshire Wolds and deposited the Chalky Boulder Clay was probably joined by ice from the Midlands, and the whole swept southwards and south-eastwards across the Jurassic and Lower Cretaceous Rocks on to the Chalk. Jurassic fossils and débris were swept as far south as Essex, but the Boulder Clay is not found on the southern side of the Thames.

It should be noted that under the North Sea Drift near Cromer one finds—

North Sea Drift.
Arctic Freshwater Bed with Arctic birch (*Betula nana*) and Arctic willow (*Salix polaris*). Placed in the Pleistocene because of its marked arctic character.
Leda myalis Bed—a local bed of sand near Cromer with arctic shells.
Cromer or Forest Beds (Pliocene).

5. Midlands of England.

At an early stage Charnwood Forest formed a local centre of ice dispersion, but was later overridden by the Chalky Boulder Clay (from the north-east). The Midlands also came under the influence of—

a. A Pennine Ice-Sheet from the North. (In Derby and Nottinghamshire the Chalky Boulder Clay is later.)
b. The Irish Sea Ice, with boulders from the Lake District from the north-west.

6. North of England (West of the Pennines).

This area was affected by—

a. Ice from the Lake District, as already mentioned.
b. Ice from the Pennine Chain.

Speaking generally, in the lower part of the Boulder Clay of Lancashire one finds far travelled boulders, whilst in the upper part fragments sheared from the neighbouring hills predominate. The deposits often fill in pre-Glacial valleys, and wisps of sand with shells are frequent.

7. Wales.

Wales was affected by—

a. Local Ice.
b. Irish Sea Ice.

a. LOCAL ICE.

(i.) At an early stage North Wales—the Snowdon Range—formed a centre of ice-dispersion and ice flowed in all directions.

(ii.) Later there was pressure from the North, and the Irish Sea ice overrode the local ice, and also flowed round it, through the lowlands of Cheshire on the east and over Anglesey to the west.

(iii.) The main centre of dispersion then seems to have been over Central Wales—in the neighbourhood of Plynlimmon—and became sufficiently important for the ice almost to override the Black Mountains and Brecknock Beacons, and also to allow the ice to pass over the northern rim of the South Wales Coalfield and into the Vale of Towy. At a later date (after the arrival of the Irish Sea Ice) it reached Pembrokeshire.

b. Irish Sea Ice.

This great ice-sheet pressed all round Wales, and pushed fossiliferous sands from the floor of the Irish Sea to great heights above sea-level. A considerable patch of apparently undisturbed sand with more than 60 species of Molluscs occurs at a height of 1,350 feet above sea-level on Moel Tryfæn. One lobe of the Irish Sea Ice passed into Cheshire and to the Midlands, another lobe crossed Anglesey, reached Pembrokeshire, and must have terminated somewhere in St. George's Channel. Icebergs which broke off from this sheet carried boulders as far as the northern shores of the Scilly Isles.

8. Ireland.

Ireland is largely covered by glacial deposits, which have given rise to much discussion. One may say—

a. that there was a number of local centres of ice dispersion;
b. that the Northern Highlands formed an early and important centre;
c. that the Northern Highlands were later overridden by ice from Scotland.

CHANGES OF LEVEL DURING QUATERNARY TIMES AND QUATERNARY COASTAL DEPOSITS (BRITISH ISLES).

1. The Pre-Glacial land level was lower than it is at the present day, and all round England we find a pre-Glacial Raised Beach, now about 12 feet above sea level. It is often covered by glacial deposits.

2. Whether it was the pressure of an enormous weight of ice or not one cannot say, but the British Isles, especially Scotland (*i.e.*, where the greatest weight of ice would be) sank at least 100 feet below sea level.

3. The gradual recovery of the land is marked by several raised beaches. The highest or 100 foot raised beach (approximately 100 feet above sea level) only occurs round the entrances of the Scottish lochs, showing that

the lochs themselves were still occupied by ice. A lower raised beach—the 50 foot—can be followed into the lochs and even round their tributary valleys, showing that the ice had then retreated to the ends of the Highland glens. On the Firth of Clyde and elsewhere beds of sand with marine shells of arctic species rest on the boulder clays. These raised beaches are also of late glacial date.

4. In the South of England, at least, the land rose well above its present level. The rivers cut themselves

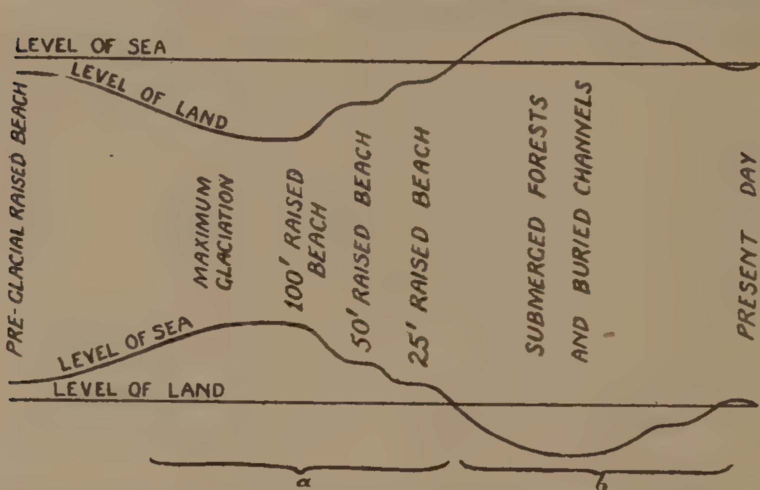

FIG. 82. Changes in relative level of Land and Sea during Quaternary Times. In the upper graph the level of the sea is supposed to remain constant, and the level of the land to change; in the lower graph the reverse is indicated. a = Phenomena observed mainly in Scotland; b = Phenomena observed mainly in England. Vertical scale, 1 inch = 300 feet. (*L.D.S.*)

deep channels, and forests grew in situations now covered by the sea. This is the period of the Submerged Forests. Remains of Neolithic man occur in the deposits of the Submerged Forests, and they belong to a late stage in Quaternary history.

5. The land then sank to its present level, and the sea flowed up the mouths of the rivers, so that most of our rivers at the present day are cutting a channel in their own alluvium, and their channel of the Submerged Forest Period is buried to a depth of some 60 feet.

The accompanying graphs show the changes in relative level of land and sea. One presumes the level of the sea to remain constant, and the change in the level of the land is referred to it; in the other the reverse is used.

In recent years several methods have been developed for the study especially of the Quaternary. One is the study of fossil pollen grains (polynology) by means of which a whole series of post-glacial stages has been determined. Another is dating by radioactive carbon. See F. E. Zeuner, "Dating the Past," London, 1946.[1]

DETAILS.

1. A Pre-Glacial Raised Beach is found at numerous points round the coasts of England and Wales, usually at a constant height of 12 feet above present high water mark.

Examples.

(a) Holderness, Yorkshire. Banked up against an old sea cliff of Chalk are beach deposits covered successively by the boulder clays and the post-glacial Sewerby flood gravels. The beach deposits yield *Elephas antiquus* and *Hippopotamus*, and are clearly of early Quaternary Age. It should be noted that they definitely underlie the glacial deposits.

(b) Selsey Bill, Sussex. The raised beach deposit contains large marine shells (*Pholas crispata*), and is overlain by a bed of large erratics (some apparently of Channel Island rocks), which were probably brought by icebergs.

(c) Cornwall. The beach deposits are overlain by rubbly drift or "head."

(d) Peninsula of Gower (South Wales). The raised beach there, with a line of old sea-cliffs at the back, has yielded an early Quaternary fauna, and is covered by glacial deposits.

(e) Similar raised beaches occur round the coasts of Ireland, Isle of Man, and also in Scotland (Colonsay, Dunbar, etc.). In Scotland, however, the raised beaches seem to be somewhat higher.

2. Apart from the general depression during the actual ice period, the glaciers seem to have scooped out great hollows, now filled with drift, especially in the mouths of some of the northern rivers (Mersey, Tyne, etc.).

3. The Raised Beaches of Scotland.

a. 100 foot Beach, not so well marked as the later ones, has yielded a markedly arctic fauna of marine shells.

b. 50 foot Beach is well marked, and often cut into hard rock. Shells indicate a colder climate than at present.

c. 25 foot Beach is also well marked, and may be backed by a line of old sea cliffs, as on the Clyde. Near Paisley "dug-out" canoes have been found and a Neolithic axe.

[1] See also A. D., Lacaille The Chronology of the Deglaciation of Scotland. *Proc. Geol. Assoc.*, vol. lxi., 1950, pp. 121-144.

Practically no trace of such raised beaches are found in England, and it is doubtful whether the land was ever depressed to such an extent. It is curious, however, that an apparent raised beach occurs at 130 feet above sea-level at Goodwood (Sussex).

4. Submerged Forests occur practically all round England and Wales, and a similar peat bed covers large areas of the North Sea (Dogger Bank). The trees are common British plants—*Betula alba* (birch), *Alnus glutinosa* (alder) and *Quercus robur* (oak). Usually there are two beds of peat separated by a silt with fresh-water shells. The upper peat has yielded Neolithic implements in several places. Latterly horizons have been determined by pollen analysis. The buried river channels will be mentioned again in connexion with the deposits of the River Thames.

THE UNGLACIATED PARTS OF BRITAIN.

The deposits of Quaternary Age comprise chiefly—

(1) Cave Deposits.
(2) River Deposits.
(3) Superficial Deposits of various kinds.

1. Cave Deposits.

Numerous Caves in the British Isles have been explored, and the following are a few selected examples :—

a. Victoria Cave, Settle.

Here the succession was :—

Talus.
Romano-British Layer.
Neolithic Layer.
Upper Cave Earth, with grizzly bear and reindeer.
Laminated Clay (? glacial mud) — Covered by Boulder Clay at the entrance to the cave.
Lower Cave Earth, with *Elephas antiquus, Rhinoceros leptorhinus*, etc. — Covered by Boulder Clay at the entrance to the cave.

b. Gower Peninsula.

Probably pre-Glacial shore caverns. They have remains of *Elephas antiquus, Hyæna*, etc., and the mouths are covered by the deposit known as "head."

c. Kent's Cavern, Torquay.

A famous cave, but puzzling in many respects. The succession of deposits is roughly—

Cave Earth, with Romano-British and Neolithic remains.
Stalagmite floor.
Cave Earth (red), with numerous bones and Palæolithic implements.
Red Breccia, with implements and bones.

The Red Breccia yielded numerous bones of bears and a few implements of Chellian type.

The Red Cave Earth varied in thickness and yielded implements of Acheulian, Mousterian, Aurignacian, Solutrian and Magdelanian types at different levels and in different parts of the cave. The depths at which the various implements were found is consistent with the scheme of age given on page 350, except that Mousterian types were found at a greater depth than any others. More remarkable, however, is the association throughout with Hyæna, Mammoth and Sabre-toothed tiger (*Machærodus*). The latter is most interesting, elsewhere it is restricted to very early Pleistocene. It may be that such warm-temperate animals managed to survive in a few sheltered caves during the glacial period —not necessarily in this one, which was occupied by man for long periods. It may be that the Cave Earth is a secondary deposit, and that the association of these bones with the flint implements is accidental.

2. River Deposits.

Whilst it is possible to determine the relative ages of the deposits of gravel laid down by one river, it is usually extremely difficult to correlate the deposits of different river systems.

The River Thames may be taken as an example of a river-system whose valley shows successive terraces, each with its deposit of gravel and "brickearth" or loam. The terraces of the lower River Thames are arranged as illustrated in the diagrammatic section (*Fig*. 83).[1]

a. THE FIRST TERRACE, up to about 130 feet or more above the present level of the river, occurs notably on Dartford Heath. The gravel contains material derived from Glacial Drift, including Bunter quartzite and Corallian chert with the sponge *Rhaxella*. This chert is only known *in situ* near Brill and at Scarborough. Remains of mammoth and flint implements of Chellian and Acheulian types occur.

b. THE SECOND OR HIGH TERRACE (100 foot Terrace) yields implements of Chellian, Acheulian and possibly Mousterian types, especially at Swanscombe and other places between Dartford and Gravesend in Kent. Associated mollusca include the extinct *Unio littoralis, Neritina grateloupiana*

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1 A new classification of the terraces of the River Thames has lately been adopted by the Geological Survey (see Guide to the Geology of London, 2nd Ed., 1922, pp. 53-9). Naturally the same terrace occurs at a greater height above sea-level as one goes up the river, and it is perhaps better to name the terraces after typical localities. It is claimed that the old "First Terrace" cannot be separated from the Second (now known as the Boyn Terrace): whilst the Third is now called the Middle or Taplow Terrace, and the Fourth the Flood-plain Terrace. For a Summary of the later classification of terraces see F. K. Hare, *Proc. Geol. Assoc.*, vol. lviii., 1947, pp. 294-339.

(with colour markings) and *Valvata antiqua*, together with various living species. Animals include *Elephas antiquus*, *E. primigenius* (mammoth), rhinoceros, deer, lion, etc.

c. THE THIRD OR MIDDLE TERRACE (50 foot Terrace) has palæolithic "floors," and yields Mousterian implements. This terrace includes the famous brickearth of Ilford and the gravels and brickearth of Crayford. Mollusca include *Corbicula fluminalis* (now only found living in the Nile), and numerous others—nearly all living. Animals include *Elephas antiquus* and mammoth, rhinoceros, musk ox, marmot, etc.

d. THE FOURTH OR LOW TERRACE (10-25 feet above sea-level) embraces the low-lying gravels of Kew, Richmond, etc. Doubtfully assigned to the period of Solutrian and Magdalenian implements.

e. THE BURIED CHANNEL. Reaches a depth of up to 80 feet below present river-level (Charing Cross).

f. ALLUVIUM (HOLOCENE) consists of clay or silt, shell-marl, peat, sand and gravel, often in alternating layers. Vivianite (phosphate of iron) is frequent. Broad tracts of alluvium occur on either side of the river, and many parts of London are built on what were, until recently, islands separated by muddy creeks (Chelsea, Battersea, Westminster, etc.). Fossils include many mammals not now living in these islands (elk, wolf and bear), but only one or two extinct (Irish elk). Neolithic stone implements and remains of the Bronze and Iron Ages occur.

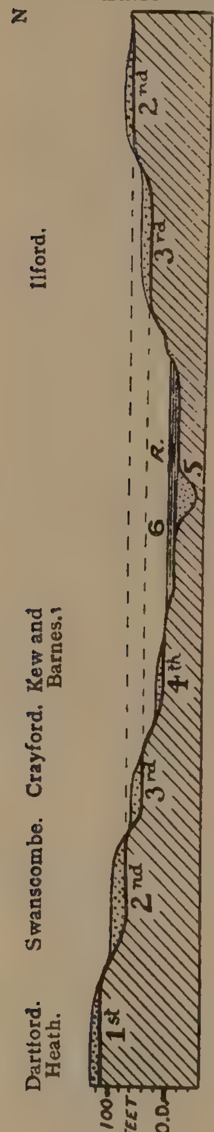

FIG. 83. Diagrammatic Section across the Valley of the Thames, showing Terraces. The first four terraces are numbered; 5 is the buried channel; 6, Alluvium, and R the present River Thames. Some of the most famous localities are indicated above. (*L.D.S.*)

It should be noted that great caution is necessary in correlating isolated patches of gravel simply by their altitude above sea level. Many quite large areas have been let down or slipped bodily to far lower levels than they formerly occupied.

3. Other Superficial Deposits.

a. CLAY-WITH-FLINTS covers a great part of the Chalk lands. It is a stiff, reddish-brown clay, with numerous unworn flints, and some derived Eocene pebbles. Is of varying age, for the most part consisting of the insoluble residue from the solution of chalk, probably transported for short distances. There is no need to postulate a glacial origin.

b. COOMBE-ROCK, found especially in North Kent and round the South Coast, is a heterogeneous mass of chalk, large flints, sands and gravels exhibiting strange contortions, and probably deposited as a half-frozen sludge.

c. PLATEAU GRAVELS. This is a name loosely applied to sheets of gravel occupying comparatively high ground, and which cannot, at present, be definitely connected with the river-gravels of existing rivers. Some of the deposits may be of the nature of outwash fans from the glaciers. For others a Pliocene age and a marine origin have been claimed. Of interest in this connexion are the patches of gravel, full of quartz pebbles, which occur at about 400 feet above sea-level to the north of London. If these gravels are early Pliocene in age (*i.e.*, lateral equivalents of the Lenham Beds) they should occupy the surface of a peneplane sloping to the north, and should have a heavy mineral composition comparable with that of the Lenham Beds. This is scarcely the case. If they are shown to occupy a horizontal plane they must be later than the Pliocene warping, *i.e*, late Pliocene or Pleistocene.

d. PEAT DEPOSITS.

i. Scotland. The following general succession in post-Glacial peat deposits has been established :—

Upper Forestian.	
Upper Peat Bog.	Peat Bog plants.
Second Arctic Bed.	Arctic plant Bed.
Lower Peat Bog.	Peat Bog plants.
Lower Forestian.	Forest Bed.
First Arctic Bed.	Arctic plant Bed (*Salix polaris*), etc.

ii. England. The Submerged Forests of the coasts and river estuaries have already been noticed.

Note on the Succession of the Superficial Deposits of the London Basin.[1]

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[1] Guide to the Geology of the London District, H. B. Woodward, 2nd edition revised by C. E. N. Bromehead, 1922, *Mem. Geol. Surv.* See also table below, pp. 350a-350b.

1. The oldest beds appear to be certain "plateau gravels." Some of these are now claimed as Pliocene. There are—

a. Definitely Pliocene—Netley, Headley Heath and elsewhere along the North Downs, and probably the Shooter's Hill Gravel.

b. Possibly Pliocene—the "400 foot Terrace"—a quartz gravel capping many hills north of London (see *Fig.* 79c).

2. Glacial Deposits.

a. Some gravels which underlie, but are closely connected with the Boulder Clay.

b. Boulder Clay.

c. Newer Glacial drift—fluvio-glacial gravel deposited by waters from the melting ice-sheet.

3. Valley Gravels and Brickearth. Gravels of the Thames 100 foot Terrace have been seen resting on "Boulder Clay" near Romford in Essex, and are thus newer. (Evidence doubtful.)

It should be noted that some geologists claim that the Boulder Clay and associated beds are later than the older terraces of the River Thames.

THE QUATERNARY MAMMALIAN FAUNAS.

The Quaternary mammals fall into four groups—

1. **Tundra species.** Few but very characteristic — Lemming, Arctic Hare, Arctic Fox, Reindeer and Musk-ox.
2. **Steppe species.** Jerboa, Steppe Marmot, Horse, Ass, etc.
3. **A group of Southern species,** some extinct. Rhinoceros (various species), Cave Lion (a variety of the modern Lion), Cave Hyæna.
4. **A group of Extinct species.** Rhinoceros, *Elephas antiquus* (early Pleistocene), *Elephas primigenius* (=Mammoth, late Pleistocene).

It is not easy to trace the movement of the Quaternary faunas.

1. There were living in the British Isles before the oncoming of the Ice Age a number of southern and extinct species (*Elephas antiquus, Rhinoceros* spp.).
2. With the oncoming of the Ice Age many creatures left these islands entirely, and retreated to the Continent. Thus these islands have an impoverished fauna when compared with neighbouring parts of the Continent, and poorest of all is Ireland. This is true whether one takes mam-

mals, reptiles or the number of species of just a single genus of molluscs, such as *Clausilia* :—

Austria	Germany	England	Ireland
150	60	4	2

On the other hand, other animals, together with man, retreated to caves (Cave lion, Cave bear, Cave hyæna, etc.).

3. Associated with the cold conditions came various animals, such as the Mammoth (*Elephas primigenius*), followed shortly by the tundra animals (Reindeer, Arctic Fox, Marmot, etc.).
4. The Steppe fauna followed, but is not well represented in the British Isles, probably owing to the relatively moist climate that characterizes these islands all through.
5. The modern fauna then became re-established. Some of its members seem to be new immigrants, others to have come out of their retreats. Thus it is very probable that the existing fauna of Ireland must have lived through the Glacial Period in some southern part of the island.

THE HISTORY OF MAN.[1]

It is often very difficult to correlate the comparatively abundant artefacts — flint implements — which man has left behind and the rare remains of man himself. The accompanying diagram of the human genealogical tree shows the probable relationships between the different types of fossil man.

The earliest tree-dwelling mammals occur in the Eocene; they were closely allied to the lemurs. True monkeys appeared later, monkeys of modern type in the Miocene, whilst the man-like apes have existed since the Middle Miocene.

1. *Pithecanthropus erectus.* "The man-like apes seem to have disappeared from Europe early in Pliocene times, when the climate of this region began to assume a temperate character, and eventually passed through the glacial period. It is, therefore, necessary to search the geological formations of more tropical

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[1] "A Guide to the Fossil Remains of Man . . . in the British Museum (Natural History)," 2nd Ed., 1918; A. Keith, "The Antiquity of Man," 1916, "A New Theory of Human Evolution," 1948; H. J. Fleure, "A Natural History of Man in Britain," 1951.

lands for the essential links between the ancestral apes and man. It seems unlikely that any of these animals would return to colder climes until they had acquired the faculty and habit of combating nature by the artificial means of clothing and fire—in fact, until they had actually become man. Unfortunately only one discovery which may perhaps be regarded as tending to fill the gap between the ancestral apes and man has hitherto been made in the tropics; and in this case the remains are so fragmentary that they admit of more than one interpretation. They comprise the roof of a skull, two molar teeth and a thigh-bone found by Professor E. Dubois in a river deposit of either late Pliocene or early Pleistocene age at Trinil, in Java." They probably belong to a single individual, and are considered by Dubois to represent a link between the gibbons and man, and named by him *Pithecanthropus erectus*. The roof of the skull is remarkably like that of the gibbons which still live in Java, but the relatively large brain capacity, the upright gait (implied by the thigh-bone) and other features are more markedly human.

2. *Eoanthropus dawsoni* (Piltdown Man). True man probably reached England by the end of the Pliocene or in early Pleistocene times. Fragments of a skull and part of a lower jaw were found by Mr. Charles Dawson at Piltdown in Sussex. The fragments of the brain case were remarkable for their enormous thickness—10 to 12 mm.—equal to twice that of modern European skulls. "Piltdown Man" presented many puzzling features, but it was not till many years later—in 1953-4—that the fragments were re-examined by modern methods. It was revealed that scientists had been taken in by a gigantic hoax. But who skilfully prepared the fragments of ape bone and caused them to be buried and found will probably never be known. In the gravels were also "found" "eoliths" (see page 345), but these were rolled and apparently derived from an older deposit, and also flint implements of very early Palæolithic type and a bone implement fashioned from the leg-bone of the late Pliocene or early Pleistocene elephant. Associated fossils include rolled Pliocene mammalia and also contemporary vertebrate remains pointing to an early Pleistocene age. Some were doubtless genuine.

3. *Homo heidelbergensis* (Heidelberg Man). The remains consist of a single lower jaw found at Mauer, near Heidelberg (hence known as the Mauer Jaw). The jaw is very strong, and marked by a retreating chin more ape-like than in any modern man.

4. *Homo primigenius* (*H. neanderthalensis*, Neanderthal or Mousterian Man). Several remains have been found of this type of man. He lived somewhat later in the Pleistocene, and seems to have inhabited caves during a cold period. His remains are associated with those of mammoth, reindeer, woolly rhinoceros, cave lion and cave hyæna and characteristic Mousterian implements. The skull is thick, and there are marked brow-ridges and a lower jaw with a receding chin. His brain capacity was slightly higher than that of modern man, but probably the brain was of inferior quality.

5. *Homo sapiens* (Modern Man). Skeletons not differing in any essential from those of modern man have been found associated with Aurignacian, Solutrian and Magdelanian implements, and point to modern man's appearance well back in the Pleistocene.

THE HISTORY OF THE ARTEFACTS OF MAN.

From a study of the implements used by pre-historic man several ages have been distinguished :—

Iron Age.
Bronze Age.
Stone Age. { Newer (Neolithic) or Polished Stone Age. Older (Palæolithic) or Chipped Stone Age. ? Oldest (Eolithic).

The interest from a geological point of view centres round the stone age.

Eolithic Period. There must have been a time when ancient man used the first stone that came to his hand as a weapon or as a domestic implement. The next stage was probably when he attempted to improve the edge of a natural stone by chipping it.

a. Certain scientists claim that such slightly "improved" natural stones can be recognized, and they are called collectively "Eoliths." The term is applied more particularly to ochreous-patinated roughly chipped flints found especially on the North Downs of Kent. The chipping often has a strong semblance of having been artificially done.

b. Other scientists claim that once man discovered that a natural stone could be improved by chipping he would produce a shaped implement which would be easily recognizable, or else that his earlier attempts would be indistinguishable from naturally chipped stones. It is frequently stated that the artificial chip can be recognized by a marked "bulb of percussion"—a low semiconical elevation, with the apex marking the point of application of the pressure or blow which removed the flake. Whilst flakes artificially removed usually show this feature to a marked degree, it cannot by itself be regarded as a positive proof of an artificial origin.

Palæolithic Period.

The material used in the manufacture of chipped stone implements in this country was mainly flint. A detailed classification of flint implements, based on the type of chipping, the degree of perfection and general form, has been devised. Where flint was abundant this classification is also a time-scale; that is to say, for example, that an Acheulian implement is older than a Magdelanian, but in districts where flint was scarce and other materials were used the type of chipping and ultimate form of the implement depends more on the materials available.

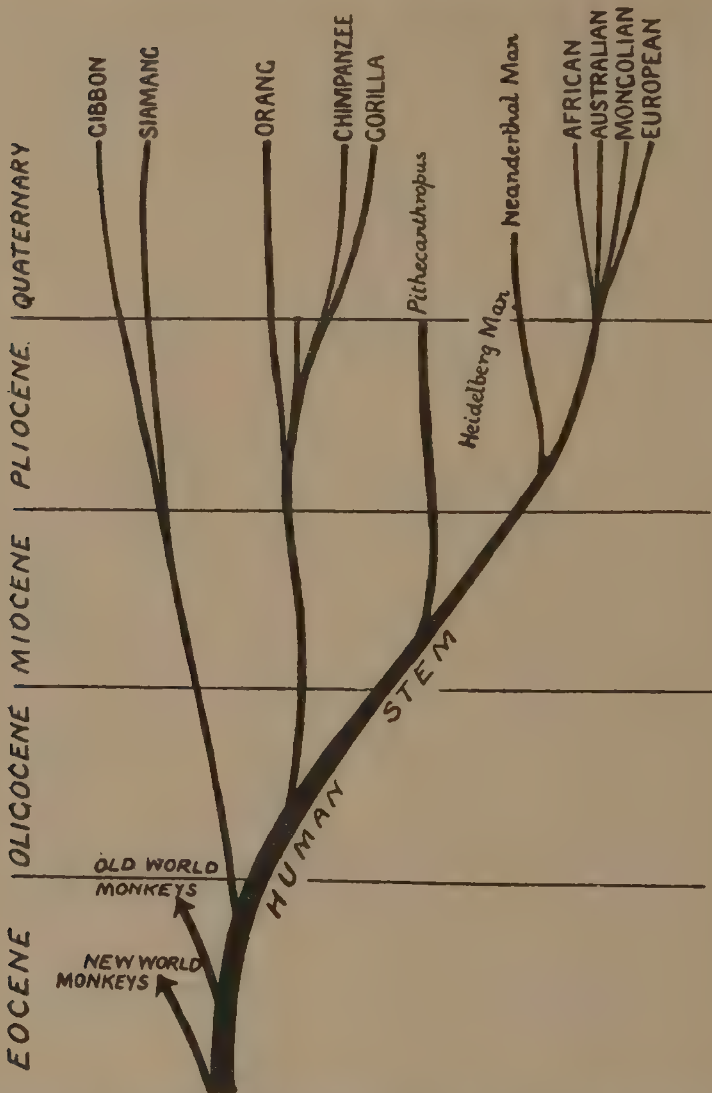

FIG. 84. A suggested Phylogenetic Tree for the Human Race (after *Sir Arthur Keith,* by permission). It will be noticed that Sir Arthur does not consider *Pithecanthropus* as a link "between the ancestral apes and man," but as an offshoot from the main stem, and similarly with Neanderthal man.

Classification of Implements.

ASYLIAN	Flat stag's horn implements. A general decline in bone and stone work. Supposed transition to Neolithic.
MAGDELANIAN	Round stag's horn implements and small light flints. Awls used. Bone-work is important and good draughtmanship.
SOLUTRIAN	Highest development of stone-work, barbed arrow points and bay-leaf knives.
AURIGNACIAN	Flint knives and points. Elongated scrapers finely worked at one end. Appearance of bone and horn implements and of drawing. Draughtsmanship very fine.
MOUSTERIAN	Broad side scrapers and flint flakes worked on one side only.
ACHEULIAN	Large hand axes (coups-de-poing), sometimes twisted, in which little or none of the original outside crust of the flint nodule can be seen.
CHELLIAN	Large hand axes, butt often formed by original crust of the flint nodule.
STREPIAN	Flint nodules chipped on certain edges, or at the points.

The first three periods (of which the earliest or Strepian is not so widely recognized as the others) constitute the Older Palæolithic or Age of River Drift Man. The implements are mainly found in river gravels, and the men who made them were probably inhabitants of the river banks. The implements are particularly well known in South-Eastern England (River Thames) and Northern France (River Seine). The fauna associated with the Chellian appears to be a warm temperate one—*Elephas antiquus* and *Rhinoceros merckii*—that with the Acheulian has a colder aspect and *Elephas primigenius* (Mammoth) appears. It seems that the oncoming glacial conditions forced man to seek the shelter of caves. Mousterian implements are found both in river gravels and in caves; implements of later periods are found very largely in caves, and hence the Later Palæolithic is also known as the Age of Cave Man. Mousterian implements appear to have been made by Neanderthal man; the associated fauna is, on the whole, a cold one (*Elephas primigenius* and *Rhinoceros tichorhinus*). On the Continent of Europe, Aurignacian and Solutrian implements are often found in loess, remains of horse are abundantly found in association with the former, reindeer with the latter. Wonderful coloured drawings of Aurignacian age are found on the walls of caverns—especially in Spain—also little statuettes which show affinities with the art and ideals of beauty current among the Bushmen of South Africa. A marked decline of implement making and art is seen in the Magdelanian, of which the associated fauna is arctic.

Neolithic Period.

This is the Age of Polished Stone. Neolithic man introduced agriculture, and he domesticated animals, he belonged to a round-

headed race, and buried his dead in round barrows. In many ways he was inferior to Palæolithic man—he had no pictorial art. Neolithic man was post-Glacial, he lived out in the open, and his implements are associated with a present-day fauna and flora. There has been great discussion as to whether there is a transition from the Palæolithic to the Neolithic Period, or whether there is a break or "hiatus" between them. Probably Neolithic men were invaders (of the Alpine Race), who conquered the decadent Palæolithic peoples. Round the coasts of Scotland, but more especially of Denmark, are great heaps of the shells of edible molluscs (kjökkenmöddingen, often translated as kitchen-middens) left by Neolithic man and his immediate predecessors. As already stated, polished stone implements are associated with the later stages of the submerged forests. Round-headed Neolithic man buried his dead—usually in a contracted position—in round "barrows" (mounds). Neolithic man was also responsible for the great megalithic buildings, such as Stonehenge.

Bronze and Iron Ages.

A discussion of the remains of these ages scarcely falls within the domain of geology.

EFFECTS OF GLACIATION IN THE PRESENT DRAINAGE.

The present drainage system of the British Isles originated in pre-Glacial times, but was extensively modified during the Glacial period.

1. Formation of lakes and tarns. These are due both to the "scooping" action of glacier ice and to the accumulation of moraine material across river valleys. A river ponded back by the presence of glacial debris, or even by an ice-lobe in the lower part of the valley, may form a lake, the waters eventually finding an outlet in quite a different direction.

2. The Glacial Lakes of Yorkshire. Yorkshire affords some now classical examples of the effect of glaciation on drainage. The natural outlet of the broad Vale of Pickering is into the sea just south of Scarborough. It would seem that this natural outlet was blocked by the North Sea Ice in glacial times, and the river waters were ponded back to form a great lake, which eventually overflowed southwards, thus producing the gorge of Kirkham Abbey. The Vale is now drained by the Derwent, which rises within a few miles of the coast at Scarborough and flows south-westwards and then southwards through this gorge.

3. A somewhat similar example is afforded by the River Severn. In pre-Glacial times the Upper Severn probably flowed northwards into the Dee. This outlet was blocked by the incoming of the Irish Sea Ice, the waters of the river were ponded back and cut out the gorge, or at least deepened a pre-existing valley, at Ironbridge.

CAUSES OF AN ICE AGE.

Numerous causes have been suggested, but few are even possible, moreover, to outline even the bare hypotheses would occupy too much space. We may note, however, that what may

be termed an astronomical cause is usually accepted. By a variation in the position of the Earth's axis, or of the eccentricity of the earth's orbit, its relations with the source of heat, viz., the sun, would be altered and glacial conditions might ensue. But such a change would almost certainly occur periodically, and whilst there is evidence of glacial conditions during past ages, it is not sufficient to justify the hypothesis.

Throughout this account of British Stratigraphy we have found no reason to postulate the action of any agents which are unknown at the present day. Similarly it would seem that an ice-age over Europe could be explained very simply without involving any causes unfamiliar to us at the present day. Without stating that this is the correct explanation, the following may be outlined :—

1. At the present day a great Ice-Sheet covers Greenland.
2. Although the greater part of Scandinavia is in the same high latitudes, it yet enjoys a comparatively mild climate.
3. We are accustomed to these facts, and immediately connect them with the present distribution of atmospheric pressure, winds and ocean currents — especially the warm North Atlantic Drift which bathes the shores of North-Western Europe.
4. Why should such special features always have been thus? We have no reason for supposing that they were.
5. The conditions necessary for the formation of an ice-cap are, very roughly, abundant precipitation, and an average temperature below freezing point.
6. Let us just presume that the Gulf Stream and its continuation the North Atlantic Drift flowed northwards between Greenland and Labrador, and that the cold arctic current swept past the British Isles. Even such a simple change might be sufficient to cause an Ice Cap such as that now found covering Greenland to cover Scandinavia.
7. In other words, the Quaternary Ice Age may be attributed to a change in meteorological conditions. That meteorological changes of a comparable character have actually taken place is attested by the desiccation of Northern Africa and Central Asia.

The possible cause of the Great Ice Age has been considered here because it naturally affects the question of interglacial periods. Briefly, the facts which have to be explained are—

a. There is definite evidence of four periods of cold separated by milder periods in the Alps.
b. There is definite evidence of at least two great periods of glaciation in Scandinavia.
c. There were great changes in the centres of ice dispersion.

Now, naturally a great change in meteorological conditions did not take place all at once. Accordingly the migration of a centre of low pressure and of great rainfall from one region to another may have caused considerable local changes on the mar-

gins of its path (*e.g.*, the Alps) which are not felt in the main track (British Isles to Scandinavia). It is interesting to note that it was long ago suggested that after the Scandinavian Ice-Cap was formed and had already reached the British Isles, the Ice-Cap in Scotland began to increase in importance, possibly due to its having intercepted some of the moisture-bearing winds.

THE GLACIATION OF SCANDINAVIA.

One of the most interesting features of the glacial deposits of Scandinavia is the evidence afforded as to the actual number of years since the ice left the country. The deposits of certain lakes exhibit alternating minute layers of coarser and finer material which are held to indicate seasonal changes in sedimentation. By counting these layers it is found that 8,000 years have elapsed since the ice left Southern Sweden. That these layers do actually represent seasonal changes is further evidenced by the fact that a small moraine can be traced, on the outside of, and terminating each double layer of sediment (*i.e.*, coarse and fine). The double layer of the previous year passes under that line of moraine, and stretches out as far as another moraine. The distance between two successive moraines gives the amount of retreat of the ice-sheet in one year.

Two main stages can be traced over Northern Europe. One, the older and of greatest extent, has left a sheet of drift, without a terminal moraine, but covered by loess. The other has left a sheet of drift bounded by a well marked moraine that stretches across the North of Germany.

Just as in England, an interesting series of surface oscillations took place in Scandinavia, resulting in the complex history of the Baltic Sea—at times a fresh-water lake, at other times a sea salter than at the present day.

THE GLACIATION OF THE ALPS.

The history of the Quaternary Period in the Alpine region has assumed special importance from the proof there obtained of the existence of four distinct ice-ages separated by interglacial periods. Most geologists admit the truth of this statement, and a great amount of study has been devoted to the object of correlating our English deposits; but it is by no means certain that the same four ice-ages could be traced elsewhere than in the Alps.

Stages.	Deposits
Fourth Inter-glacial	Post-glacial to present.
Würm Ice-age	Low Terrace gravel. *E. primigenius.*
Third Inter-glacial	Loess } Mousterian implements occur associated.
Riss Ice-age	High Terrace gravel }
Second Inter-glacial	*Elephas antiquus* and *E. meridionalis* still occur.
Mindel Ice-age	Younger Deckenschotter.
First Inter-glacial	
Günz Ice-age	Older Deckenschotter.

It has been shown that in the Inter-glacial periods the ice retreated further up the valleys than at the present day and a comparatively warm-temperate flora characterizes the deposits.

THE CHRONOLOGY OF THE QUATERNAR

East Anglia	Lincs and Yorks	Upper Thames Vall
	Arctic peats and plant beds	
Hunstanton brown boulder clay	Hessle boulder clay Later retreat of Dales glaciation York moraine	Deep channel filled base Flood-plain gravels
Hill washes, river silts and brickearths Morston raised beach	Marine shingle ? raised beach sands	Excavation of deep channel Erosion Hill washes
Upper chalky drift	Upper purple boulder clay Main Dales glaciation Vale of York maximum	Warp, frozen soil, of Wolvercote chan
Early Mousterian brick-earth Upper Acheulian gravels Brickearth and river gravels	Sands, gravels and laminated clays with *Corbicula fluminalis*	River clays and pe Lower gravels of W vercote channel Upper Summertown terrace Lower Summertown terrace
Chalky-Jurassic and Chalky-Neocomian boulder clay Contorted drift	Lower purple boulder clay Early Dales maximum	Wolvercote terrace
Glacial sands and gravels	Gravels and sands	100-140 ft. terrace Handborough terra
Norwich brickearth ? Cromer Till Cromer Forest Bed	Basement clay Sewerby beach and cliff	Plateau gravels

★ The Clactonian and Levalloisian cultures

CCORDING TO P. G. H. BOSWELL (1932)

Lower Thames Valley	Industries	
		?5th Glacial
		? Inter-glacial
Lea Valley, Ponder's End stage	? Magdalenian and later	4th Glacial
Erosion Later Coombe rock	Aurignacian	3rd Inter-glacial
Coombe rock	Mousterian ★	3rd Glacial
Upper Crayford brickearth Lower Crayford brickearth Taplow (50ft. terrace 100ft. terrace	.... Acheulian ★	2nd Inter-glacial
Chalky-Jurassic boulder clay	Chellian	2nd Glacial
		1st Inter-glacial *
	Pre-Chellian	1st Glacial

ontemporaneous with Acheulian and Mousterian.

ECONOMIC GEOLOGY OF THE QUATERNARY.

1. Building Stones. Calcareous Tufa, deposited by springs in some limestone districts, is occasionally used. The larger stones from superficial gravels, etc., are often used locally for rough work, walls, etc.

2. Road Metal. Superficial gravels, especially flint gravels in the South-East of England, are quarried extensively, and the coarser material is used on by-roads. Finer gravel, with sufficient clayey matter to make it "bind," is much in demand for garden paths, etc. Often a gravel is graded by screening, the intermediate grade being used in concrete work. In recent years the extended use of concrete in many forms of construction has given rise to an enormous demand for gravel, especially river gravel.

3. Sands. Many gravels include lenticles of sand, the grains of which are angular and less rounded than in older sands. This is especially true of sands consisting of small flint chips, the angles of which are rounded by solution in older deposits. Such "sharp" sands are of great value in building. Some pure sands, suitable for glass manufacture, also occur in Quaternary deposits. They are of two kinds (a) glacial sands interbedded with Boulder Clay as Lancashire (*e.g.*, St. Helens' glass-making centre) and near Ipswich (moulding sand); (b) pockets of sand often of doubtful age occurring in solution hollows, especially in the Carboniferous Limestone of Derbyshire.

4. Clays. Superficial deposits of very variable characters have been used for brick-making, notably the Thames Brickearth, Clay with Flints (more locally), some Boulder Clays and Alluvium. These local industries have suffered largely from the centralizing of the brick-making industries (see page 246). The use of river muds in the manufacture of cement has already been noted.

5. Peat. Superficial peat deposits are extensively utilized for fuel in Ireland, and to a less extent in Scotland and Wales. Various efforts have been directed towards the greater utilization of our vast supplies of peat, notably in the production of commercial alcohol, and in the preparation of "Bacterized Peat," a valuable nitrogenous manure. But success has varied.

6. Kieselguhr (Diatomaceous Earth). Valuable as an absorptive in dressing wounds, and of importance in the manufacture of certain non-conducting bricks, this substance is obtained in County Antrim (North of Lough Neagh) and in Scotland.

7. Bog Iron Ore. Occurs to a small extent in Ireland and Scotland.

8. Water Supply. Superficial deposits of gravel have been a very important factor in deciding the position of towns. Many tracts of clay (*e.g.*, Oxford Clay) are practically without a town, except where areas of superficial gravel occur (Oxford). This is mainly the result of superficial water supply and springs afforded by the gravels. London grew out along tracts of gravel and lines of springs. Unfortunately such supplies of water quickly become contaminated, but the gravel tracts assume a new importance from the sanitary point of view. Everyone is familiar with the advantages of a "gravel soil" in which water circulates freely.

over a waterlogged, stagnant "clay soil." The famous old springs —many of them medicinal—which issued from superficial gravels in the London district and elsewhere are now little but legendary. It is of interest to note that many of the towns which originally drew their water supply from local gravels now rely on the rivers —a notable example being London.

9. Scenery and Agriculture. Superficial deposits, it may be relatively very thin, often alter the whole character of a country-side. What could be more noticeable than the thick coppices of oak and hazel which occur on the patches of clay-with-flints in the midst of a treeless expanse of rolling downs on bare chalk? On the whole, sands and gravels with little clay give rise to sterile but picturesque lowland heaths but gravel with a clay mixture to fertile cultivated land; boulder clay varies. Sometimes it has a sufficient percentage of calcareous material and stones to furnish a fine, naturally "blended" soil; at other times it gives rise to a cold, stiff, water-logged clay. The stretches of alluvium are often marshy, but reclaimed salt-marshes furnish some of the finest grazing ground in the country.

CHAPTER XX.

CONCLUSION—HINTS IN THE STUDY OF STRATIGRAPHY.

The study of Stratigraphy is essentially an outdoor one. To be thoroughly appreciated facts must be verified in the field, and no amount of reading can take the place of practical observation. If this little book has left the reader with the impression that arm-chair knowledge will make him a stratigrapher, it has done more harm than good. At the same time a knowledge of stratigraphy is essential in every branch of the science of geology, and one is brought back to the fundamental truth that outdoor work must be undertaken by everyone who aspires to become an efficient geologist. Happily, too, a knowledge of stratigraphy opens up a new world. Old and familiar scenes take on a new aspect, one's summer holiday may have yet another attraction, and even a tiresome railway journey may be enlivened with a new interest. Every hill and vale has its store of secrets, silent witness of a thousand changes. Without practice and without guidance the unfolding of the story may prove—in fact must surely prove—no easy matter. Fortunately excellent summaries of the geology of most parts of England and Wales and parts of Scotland are to be found in the pages of the Proceedings of the Geologists' Association.[1] In this connexion some remarks as to the Association may not be out of place. The Geologists' Association exists primarily for furthering the study of geology in the field. It organises whole-day or half-day excursions and visits to museums and other places of geological interest on Satur-

[1] Indexes to vols. i.-xx., and to each successive ten volumes, are to be obtained from the Association.

days throughout the year, as well as trips of a week or a fortnight three times yearly — at Easter, Whitsun and later in the summer. The knowledge and experience of the professional geologist or the local specialist are freely placed at the disposal of the amateur and the student, whilst the publications of the Association afford a permanent record of immense value to the field geologist. In comparison with the benefits received the annual subscription—one pound—is absurdly low, and anyone interested in the practical study of geology is strongly advised to communicate with the Hon. Secretary, Geologists' Association, c/o Geological Survey, London.

The bulk of original geological work in the British Isles is published in the "Quarterly Journal of the Geological Society," the "Geological Magazine," and in the official publications of the Geological Survey. The Geological Society of London is the premier geological society of England, and, indeed, of the world. The Geological Magazine (monthly) is an independent organ, marked by a praiseworthy lack of bias in matters of publication and an encouraging consideration for budding geologists. The Geological Survey not only publishes a fine series of colour-printed maps on the scale of one inch to one mile with descriptive memoirs—unfortunately the series for England is far from complete, and one has to use the old hand-coloured maps often without memoirs—but also numerous publications of a more general nature. Especially important are the eighteen parts of British Regional Geology covering all the regions of Britain. Other maps issued by the Survey include the colour-printed sheets—complete for England and Wales—on the scale of four miles to the inch, and a very useful coloured index map of the British Isles on the scale of 25 miles to the inch at a moderate cost. Even more useful is the magnificent map of Britain in two sheets on the scale of 1:625,000 or approximately 10 miles to one inch. There are also maps of coal-mining districts on the scale of six inches to one mile. A full list of the Survey's publications may be obtained from Messrs. Edward Stanford, 13-14, Long Acre, London, W.C.2. Another useful guide is A. Morley Davies' "Local Geology," published by Thos. Murby & Co.

The storehouse of plates and descriptions of fossils is the series of memoirs of the Palæontographical Society. Unfortunately the gaps are many, and the correct naming of a single fossil may entail days or even weeks of research, or the task may be beyond the ability of any but the specialist. Fortunately there is a delightful and universal brotherhood amongst geologists, and whilst beginners are asked not to worry the specialist unnecessarily, it is rarely that a helping hand is refused. It has never yet been the writer's misfortune to receive anything but cordial and ungrudging help from a fellow geologist. In naming fossils the museums must not be forgotten — especially the storehouses of National treasures.

Other sources of information which must not be neglected are the local volumes prepared for meetings of the British Association; the publications of the Royal Society, the Royal Society of Edinburgh, local societies, and notably the Geological Societies of Edinburgh and of Glasgow; and foreign geological societies. There are several important works published by the British Museum.

Of books, it is not the writer's purpose to give here a bibliography. Geological books, like most other scientific works, are apt to become rapidly out of date. Too often stratigraphical text-books tend to be soulless compilations which become deadly dull as they lack a unifying principle or conception. The most useful are the two volumes, one on Ireland and the other on Britain, published by Thos. Murby & Co. (the publishers of this book) under the title of a Handbook to the Stratigraphical Geology of Ireland and Great Britain respectively. Each is written by a group of specialists. Amongst other text-books of wider scope than the present work may be mentioned Jukes-Browne's "Student's Handbook of Stratigraphical Geology" (1912); the same author's "Building of the British Isles" (4th Ed., 1922); A. Geikie's "Text Book of Geology" (vol. ii., 1903), and more recently L. J. Wills' "Physiographic Evolution of Britain" (1929), and "A Palæogeographical Atlas" (1951). For neighbouring parts of the Continent there is a wealth of information in M. Gignoux' "Géologie Stratigraphique" (3rd Ed., 1943) and in Lemoine's "Géologie du Bassin de Paris."

It is essential for the British geologist to maintain an interest in the international aspects of his subject. To keep for Great Britain her rightful place amongst the nations of the world even in the domain of Geological Science is an object which the writer hopes all his readers will keep in view.

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I. AUTHORS

II. FOSSILS

III. LOCALITIES

IV. STRATIGRAPHICAL DIVISIONS

V. MISCELLANEOUS, INCLUDING ROCKS AND MINERALS

GEORGE ALLEN & UNWIN LTD
London: 40 Museum Street, W.C.1

Auckland: Haddon Hall, City Road
Sydney, N.S.W.: Bradbury House, 55 York Street
Cape Town: 58–60 Long Street
Bombay: 15 Graham Road, Ballard Estate, Bombay 1
Calcutta: 17 Chittaranjan Avenue, Calcutta 13
New Delhi: 13-14 Ajmere Gate Extension, New Delhi 1
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